



AMAX
Minerals+Energy

March 22, 1988

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Superfund Branch
Waste Management Division
U. S. Environmental Protection Agency
Region VII
726 Minnesota Avenue
Kansas City, Kansas 66101

RECEIVED

MAR 24 1988

Re: Cherokee County CERCLA Site

REMD SECTION

Dear Ms. Fuerst:

As you were informed during the November 5, 1987 meeting with the Cherokee County potentially responsible parties (PRPs), seven of the PRPs (AMAX, ASARCO, Eagle-Picher Industries, Gold Fields Mining Corporation, NL Industries, St. Joe Minerals Corporation and Sun Company) have retained the services of Dr. Ernest E. Angino to prepare a report concerning premining conditions at the above-referenced site. That report, entitled "Pre-mining Surface and Shallow Groundwater Quality in the Vicinity of Short Creek, Galena, Kansas," has now been completed, and it is submitted with this letter for inclusion in the administrative record for EPA's response actions at the Cherokee County site (including, without limitation, the alternative water supply (AWS) operable unit feasibility study (OUFS), and the groundwater/surface water OUFS).

In brief summary, the report concludes, based on several independent but related approaches, that prior to mining, the surface water and shallow groundwater in the vicinity of the Galena subsite would not have met current drinking water standards or surface water quality standards. In particular, the report concludes, based on universally applicable geochemical reactions, that naturally elevated background levels of metals and other parameters existed prior to mining activities in the Galena area, due in large measure to the presence of



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an exposed oxidizing sulfide ore body. Those conclusions were supported by examination of water quality conditions at or in the vicinity of undisturbed sulfide ore bodies currently existing in a variety of climatic and geological settings around the world, and by a computer simulation of pre-mining water quality that takes into account various solubilities and oxidizing/reducing conditions. Significantly, the report supports the conclusions about pre-mining geological conditions and geochemical processes that were set forth in the report prepared by Daniel R. Stewart and submitted for inclusion in the administrative record under cover letter dated July 15, 1987.

The report clearly supports the PRPs' position that natural background conditions alone can account for the elevated metals levels that appear to exceed drinking water standards in a relatively small percentage (10 percent) of the shallow aquifer wells sampled by EPA. The information set forth in the Angino report also provides further support for the PRPs position that, based on an objective evaluation of all relevant geological, geochemical, and other factors, the "no action" alternative is the only appropriate decision for the AWS OUFS.

Accordingly, based on the information in the Angino report, the PRPs specifically request the Agency to reconsider its selection of the remedial action alternative as set forth in the December 21, 1987 Record of Decision for the AWS OUFS. This request is further supported by the fact that in the groundwater/surface water OUFS, EPA has both implicitly and explicitly acknowledged the validity of certain other comments previously made by the PRPs concerning the AWS OUFS -- despite the fact that the PRPs points were not acknowledged in the "Community Relations Responsiveness Summary" for the AWS OUFS.

For example, certain water quality data in the groundwater/surface water OUFS is treated differently than in the AWS OUFS. In our comment letter on the Final Technical Memorandum, Site Wide Water Supply Inventory (letter to Alice Fuerst dated February 1, 1988), which served as the primary support for the AWS OUFS, we noted that the average concentrations of the metallic ions in the 123 private wells sampled were erroneously calculated and that this action distorted the description of the existing conditions and the public health assessment included in the AWS OUFS. Although this point was not acknowledged in the "Community

Relations Responsiveness Summary" for the AWS OUFS, the EPA did recalculate the average concentration of these ions in the wells for the Groundwater and Surface Water OUFS. Comparing Table 3-1 of the AWS OUFS with Table 3-2 of the groundwater and surface water OUFS clearly acknowledges the validity of our comment on this point.

In addition, there are other inconsistencies between the two OUFS documents including, for example, the percentage of the Galena subsite surface area that is alleged to be covered with mine waste. On page 2-13 of the AWS OUFS, the EPA stated that "an estimated 20 to 30% of the 18 square mile subsite area is covered by mining waste materials". In our comment letter on the AWS OUFS (letter to Alice Fuerst dated December 10, 1987) we noted and provided technical support for the fact that the AWS OUFS greatly overstated the area affected by historical mining activities. In the "Community Relations Responsiveness Summary" the EPA restated their position that 20-30% of the subsite was covered with waste materials, yet on pages 6 and 2-17 of the groundwater and surface water OUFS the EPA stated that "mine wastes cover about 8% of the area within the Galena subsite". These and other differences between the AWS OUFS and the groundwater and surface water OUFS clearly demonstrate that the EPA acknowledges certain inaccuracies in the AWS OUFS.

The cumulative effect of the information provided in the Angino report -- or implicitly acknowledged by EPA in the groundwater/surface water OUFS to have been inaccurate at the time of the AWS OUFS ROD -- is a fundamentally flawed decision by the Agency. Because, to the best of the PRPs knowledge, the remedial alternative selected by EPA has not yet been implemented and, at best, is still in its very early organizational stage, the PRPs believe that this request for reconsideration is both timely and warranted.

The PRPs urge the Agency to act on this request as expeditiously as practicable, to avoid the unnecessary expenditure of CERCLA funds. We also request that the instant request for reconsideration be placed on the agenda for the March 30 meeting with the PRPs in Kansas City, previously scheduled in order to discuss the groundwater/surface water OUFS.

Thank you for your consideration of this request, and for the inclusion of this letter and the Angino report in the administrative record for the Cherokee County site. As in the past, this submission by the PRPs is

not an admission or waiver of any defense (and should not be construed as an admission or waiver) concerning any PRPs liability for response costs at the Cherokee County site or concerning the propriety of EPA's activities there.

Sincerely,

A handwritten signature in cursive script, reading "Peter Keppeler".

Peter Keppeler
on behalf of

cc: Kansas Department
of Health and
Environment

AMAX Inc.
ASARCO
Eagle-picher Industries
Gold Fields Mining
Corporation
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Premining Surface and Shallow Ground Water Quality in the
Vicinity of Short Creek, Galena, Kansas

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Premining Surface and Shallow Ground Water Quality
in the Vicinity of Short Creek, Galena, Kansas

Executive Summary

This report presents an assessment of the premining surface and groundwater quality in the Short Creek, Galena, Kansas area. The assessment is based on several approaches: 1) An extensive review of the historical literature of the area as it applies to the geology, the stream water, and the shallow ground water systems of the Galena, Kansas area. 2) A review of local geology as it affected the premining natural water chemistry of the area. 3) A comparison of the effects of a sulfide ore body on water quality at Galena to that of comparable ore localities elsewhere in the world. 4) Modelling of the solubility relations for Pb, Zn, Cd in Short Creek and shallow ground waters (including springs).

From the data obtained, a comparison was made relating the known and measured values of the geochemical components of interest (pH, Pb, Zn, Cd, etc.) in the water to what must have existed in the water at Galena, Kansas during premining time. The tabular data presented shows that the metal concentrations measured in unmined but similar mineralized areas elsewhere are comparable to those computed and reported for waters of Galena, Kansas in premining time. A conservative approach was used in all computations and comparisons presented. It is clear on theoretical and scientific grounds that the surface and shallow ground water quality of the Galena area in premining time was not pristine. It assuredly was not comparable to present-day recommended drinking water standards, anymore than are those waters flowing over and through similar (known) present-day sulfide ore bodies in other localities.

CHAPTER I

Introduction

The major objective of this report is to provide in so far as possible an assessment of the premining surface and ground water quality in the vicinity of Short Creek, Galena, Kansas (Fig. 1). This assessment is based on several approaches to the problem. Key among these are:

1. A review of the pertinent historical literature of the area, especially as it applies to the premining water chemistry (surface and ground water) of the vicinity.

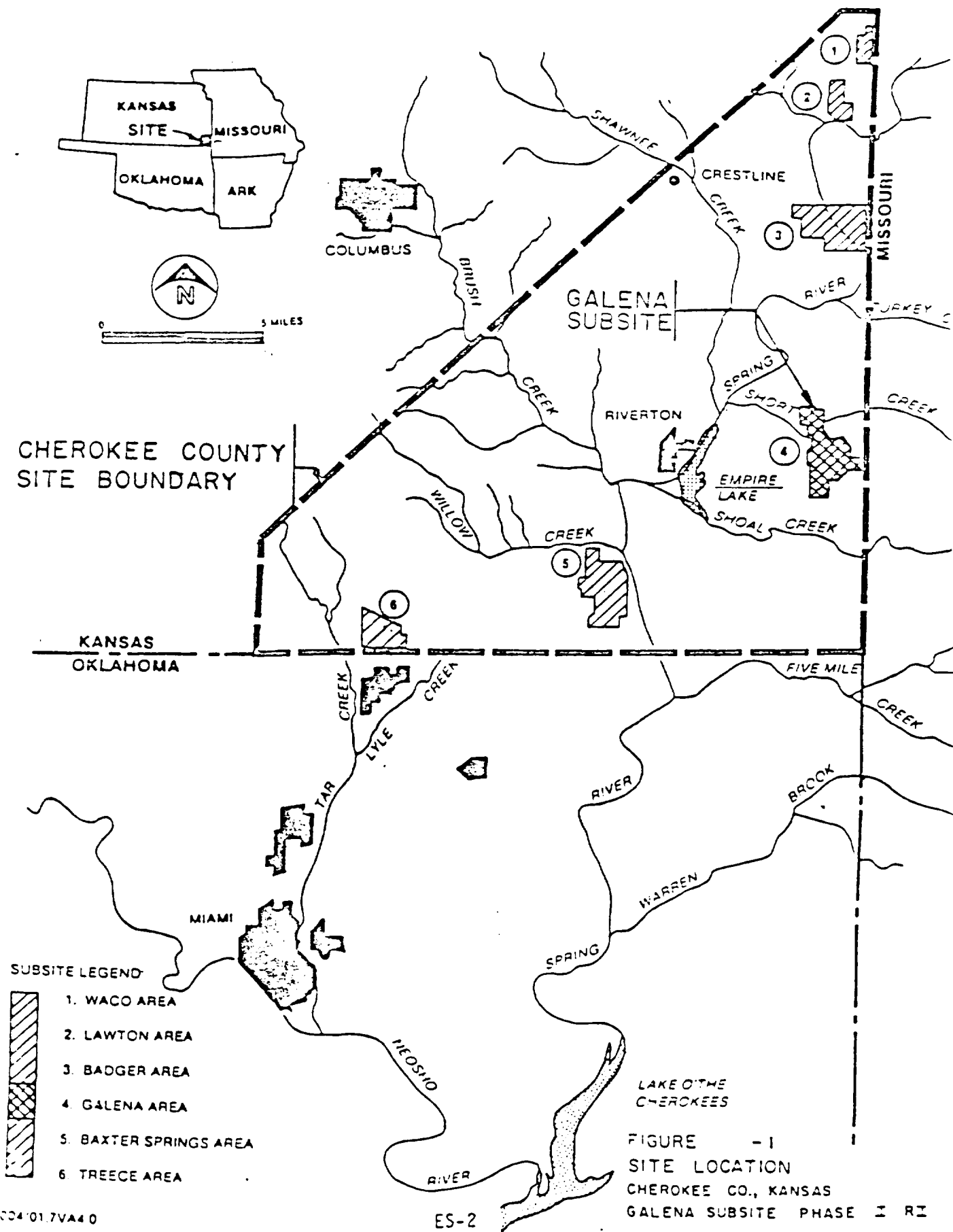
2. An assessment of the general geology of the area as it affected the water chemistry.

3. An assessment of the possible solubility levels of selected minerals (galena, sphalerite, etc.) in waters approximating the general chemistry of those in the area.

4. A comparison of the local premining geology and ore deposit mineralization to other areas in the world of either similar geology, conditions, or mineralizations. This approach should provide an indication, based on the natural laws of geochemistry as to what concentration levels of Zn, Pb, Cd, etc. could have existed in local waters in premining time.

5. A brief review of spring waters in the general area. Springs provide a natural sample and representation of the shallow ground water moving in the regional hydrologic cycle of the area.

Mining was initiated in southeast Kansas, and more specifically the Galena, Kansas area, over 100 years ago. While



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it is difficult to determine exactly what the premining water quality of the area was, in all specifics, it is possible to use published data of the era as a clear indication of what those conditions were. Coupled with modern computer modelling techniques of equilibrium and near equilibrium conditions in water of the area, it is possible to predict what likely concentrations of zinc, lead and other ions were present in solution at the time. This can be done with reasonable certainty and confidence as to the results - using acceptable modelling codes, and appropriate thermodynamic data.

For clarity, the report is broken down into several chapters. The work was done by a four person team coordinated by E. Angino. Appropriate material was provided by each person as indicated. The team consisted of E. E. Angino, geochemical comparisons (Lawrence, Kansas), Horace Jeffrey, shallow ground water (Rolla, Missouri), Robert Leonard, general geology (Lawrence, Kansas), and Donald Runnells, modelling (Boulder, Colorado). The results are predicated on the best efforts available in the time frame provided--essentially Nov. 1, 1987 to Dec. 15, 1987. The report was prepared by E. E. Angino who also conducted the historical review, and provided the general assessment contained herein from the material supplied. Resumes of these individuals are provided in the appendix.

This study is based on an extensive review of the historical literature of the area and on the subject of water quality as it applies to Short Creek and Galena, Kansas. It includes computer modelling runs based on a widely used water chemistry program

known as PHREEQE. The study was broken down into several tasks which fall naturally under the respective objectives noted.

As a part of this comparison, we can relate the known and measured values of the geochemical components of interest (pH, Pb, Zn, etc.) in the water to what must have existed in the water of the Galena, Kansas area during premining time. It is reasonable to expect that the laws of chemistry and geochemistry, when compared to situations elsewhere in the world, are applicable as well to the Galena, Kansas region. All of these tasks and factors have been woven into each chapter in one way or another.

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CHAPTER 2

Area Description

Location

The overall objective of the project of which this investigation is a part is to assess the premining surface and shallow ground water quality in the vicinity of Short Creek, near Galena, in southeastern Kansas. The purpose of this chapter is to describe briefly the general geology of the Short Creek and Galena Kansas area environs and geologically similar adjacent areas, with emphasis on the occurrence of lead-zinc ores, and their relation to the occurrence, quality, and migration of shallow ground water.

The mineralized area under discussion, the Galena Field or camp in Cherokee County, southeastern Kansas, is part of the Tri-State Lead-Zinc Region, situated on the northwest flank of the Ozark uplift (Fig. 1). To facilitate description, the mapped area shown in Figures 1 and 2 has been expanded to include all of township T34S, R25E. The principal area of interest is the southeastern part of the township which lies within the Springfield Plateau section of the Ozark Plateaus Province. It is roughly bounded by the Kansas-Missouri boundary on the east, Shoal Creek on the south, and Spring River on the northwest, and is typical of the rolling prairie land to the north and east (Figs. 2, 3).

Historical Considerations

A limited area between Short Creek and Shoal Creek, both westerly flowing tributaries to Spring River, was extensively

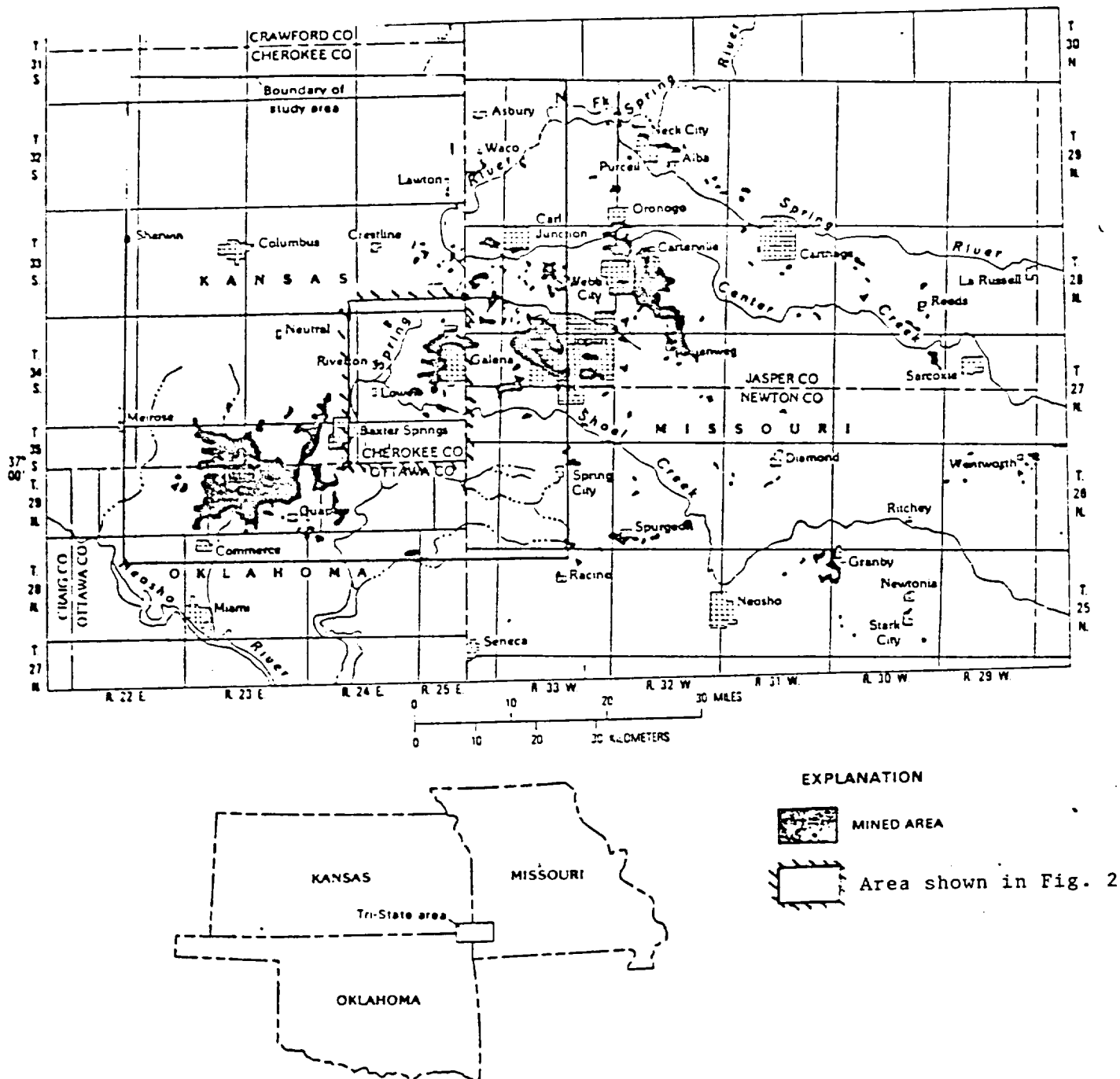


Figure 1. Principal part of Tri-State lead-zinc district, mined areas, and location of study area (modified from Feder and others, 1969).
(In Spruill, 1987, p. 3)

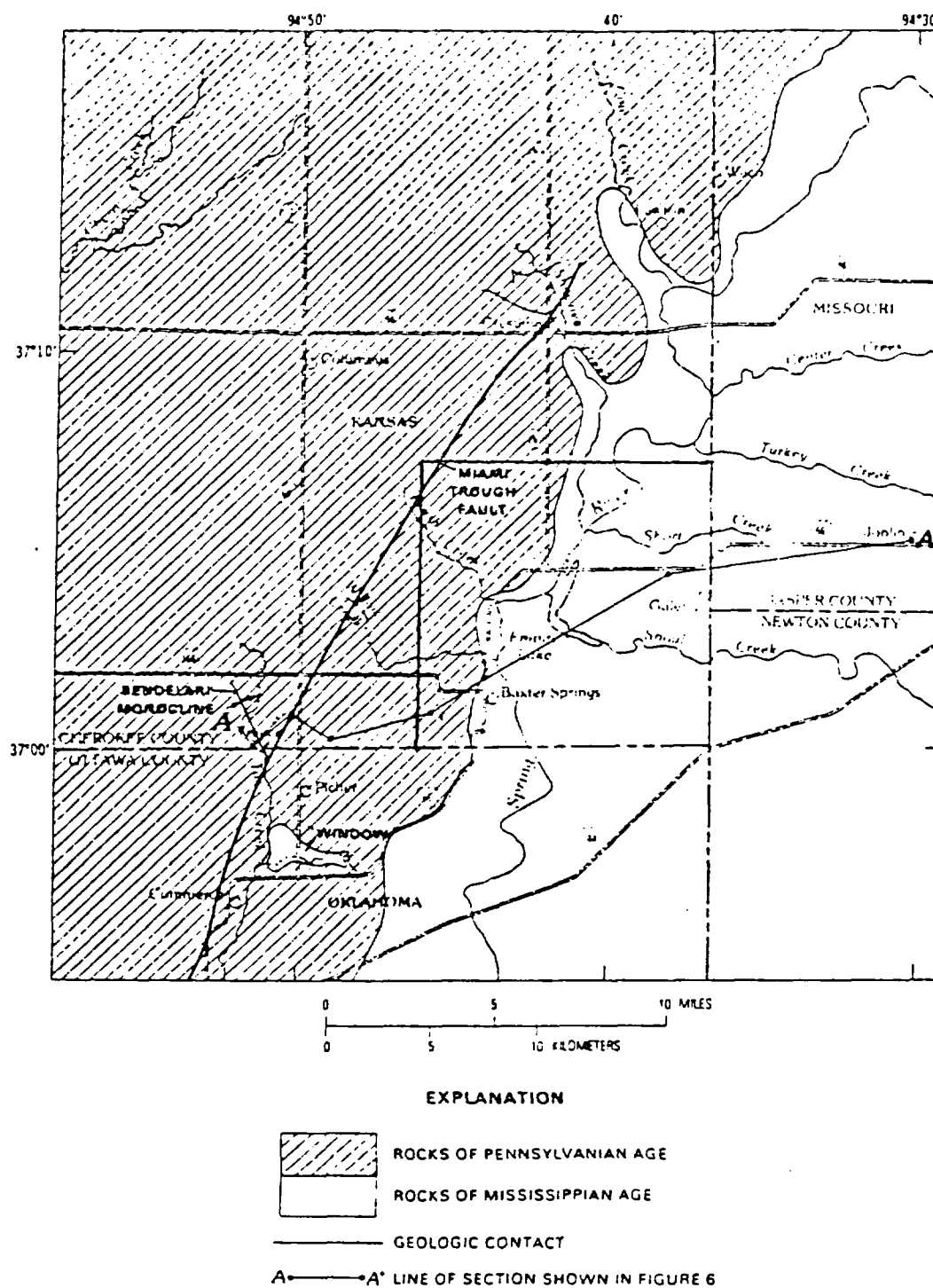


Figure 2 Generalized geologic features of study area (modified from Brichta, 1960, and Spruill, 1987)

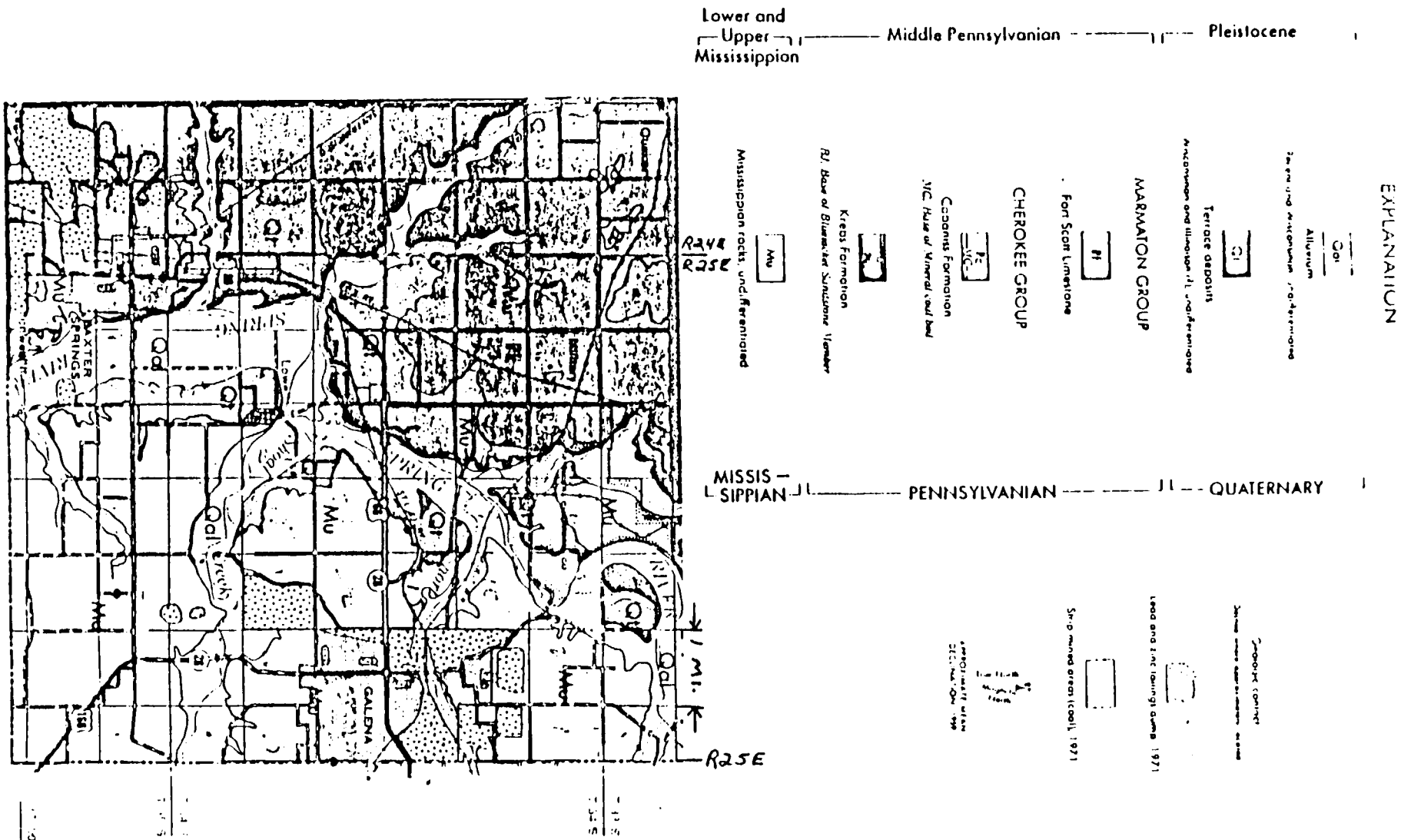


Figure 3. Generalized geologic map of the study area (modified from Seevers, 1975).

mined for lead and zinc between 1877 and 1945, when most of the mines were abandoned. Most of the mining in the Galena area occurred early in this period. The area was first known as the Short Creek mining district, considered an extension of the Jasper County, Missouri subdistrict, and part of the Joplin District. According to Winslow (1894, p. 597), the first discovery of ore in this district was in 1868 in a well. During the first few years of operation, lead ore was the principal mineral mined, but by 1883 interest in mining of zinc ore increased as better milling techniques became available (Winslow, 1884, p. 596-600). Local erosional relief is minor but can reach as much as 100 feet in places. Waste piles from milling operations associated with past lead and zinc mining, are common man-made features of the landscape. Data describing the Galena area itself are scattered through the literature. More abundant data from geohydrologically similar areas in southwestern Missouri were used in the literature review. Information obtained from recent water-assessment reports (Spruill, 1987; Macfarlane et al., 1981; Macfarlane and Hathaway, 1987) and by oral communications with the authors as part of the review process, was also particularly useful.

Geology

Within the study area, the ore occurred almost exclusively in rocks of Mississippian age, in cherty parts of the Fern Glen, Keokuk, and Warsaw limestones (Table 1) which underlie the Short Creek area at or near the land surface. The Warsaw limestone crops out on hills near Galena.

TABLE 1.—Generalized columnar section of the surficial rocks in Cherokee County, southeastern Kansas.

System	Series	Stage		Geologic unit	Average thickness (feet)	Description
Quaternary	Pleistocene	Recent and Wisconsinan		Alluvium	30	Silt, and silty sand, gray to grayish-brown, limonite stained in part; contains some sand and medium to coarse gravel at base.
		? — ? Wisconsinan and Illinoisan (?)		Terrace deposits	25	
Pennsylvanian	Middle Pennsylvanian	Desmoinesian		Fort Scott Limestone	20	Limestone, light-gray to brownish-gray, and black to light-gray shale
				Cabaniss Formation	225	Shale, light- to dark-gray; contains siltstone, limestone, sandstone, and coal. Commercially most important coal beds in Kansas occur in this formation.
				Krebs Formation	225	Shale, light- to dark-gray, and fine- to medium-grained sandstone; contains coal, underclay, siltstone, and some limestone locally.
Major unconformity						
Mississippian	Upper Mississippian	Chesteran		Undifferentiated rocks of Chesteran age	120	Limestone, shaly, and calcareous shale; contains some oolitic limestone and sandy shale.
		Meramecian	FM.	Warsaw Limestone	120	Limestone, crinoidal; contains much gray chert. Base marked by glauconite-rich layer known locally as the "J-bed". Contains deposits of lead and zinc of commercial value.
	Lower Mississippian	Osagian		Keokuk Limestone	130	Limestone, medium to coarsely crystalline, bluish-gray, and gray chert; contains oolitic limestone near top. Cherty parts weather to characteristic reddish-brown color. Contains deposits of lead and zinc of commercial value.
				Fern Glen Limestone	170	Limestone. Reeds Spring Limestone Member (upper unit) is cherty, finely crystalline, bluish-gray. Contains deposits of lead and zinc of commercial value. St. Joe Limestone Member (lower unit) is crinoidal, dolomitic in part, green.
		BOONE				

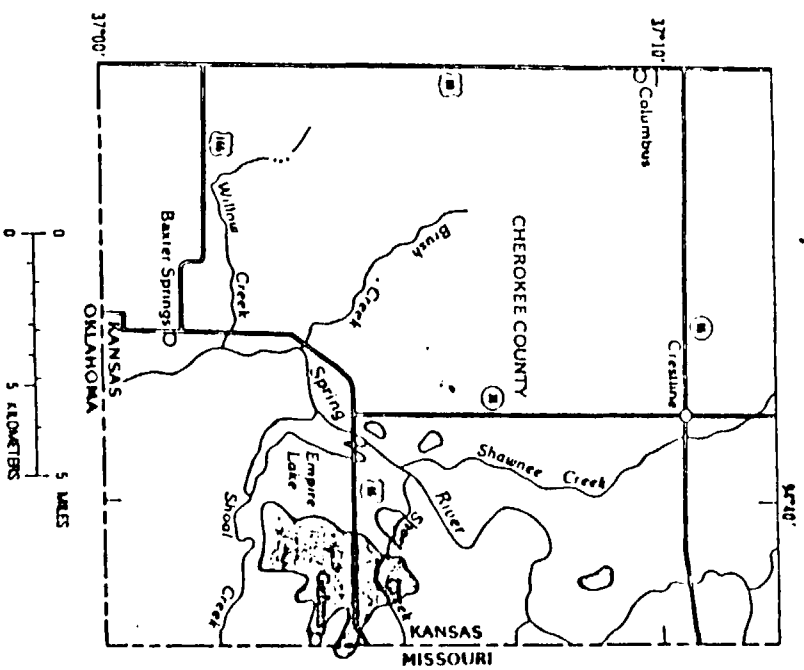
Modified from Seevers, 1975.

The interval is collectively referred to as the Boone formation in Oklahoma and Missouri, or as the Boone Chert, because the interval consists largely of chert and cherty limestone and is commonly represented at the surface as a residual soil largely composed of angular chert. Because the components exhibit somewhat similar lithologic and hydraulic properties, they are collectively included in the "undifferentiated Mississippian series" by Macfarlane and Hathaway (1987) and the "shallow aquifer" by Spruill, 1987.

The Mississippian rocks dip to the northwest at approximately 10-20 feet per mile (slightly greater than the slope of the land) to the vicinity of Spring River, where they are unconformably overlain by shale, the Krebs formation of Pennsylvanian age. There, water in the Mississippian rock is under artesian conditions, whereas in the study area to the east, water table conditions generally prevail (Figs. 2, 5).

Winslow (1894, p. 157) stated that the ore zones "consist largely of fragments of chert, in places cemented by a dark quartzose matrix, the so-called brecciated zones of Haworth (Fig. 4). Elsewhere, the spaces between the chert fragments are filled with clay, sand, and other residuary products. In this material the metallic minerals are found. They consist principally of zinc blende (sphalerite), and galena. These deposits belong geologically and commercially to the Joplin district of southwestern Missouri and are in all essentials similar to the latter."

As a result of uplift and exposure of the Mississippian



EXPLANATION

 BRECCIATED ZONE

Figure 4. Location of major brecciated zones in eastern area in Kansas (modified from Haworth, 1904; Spruill, 1987).

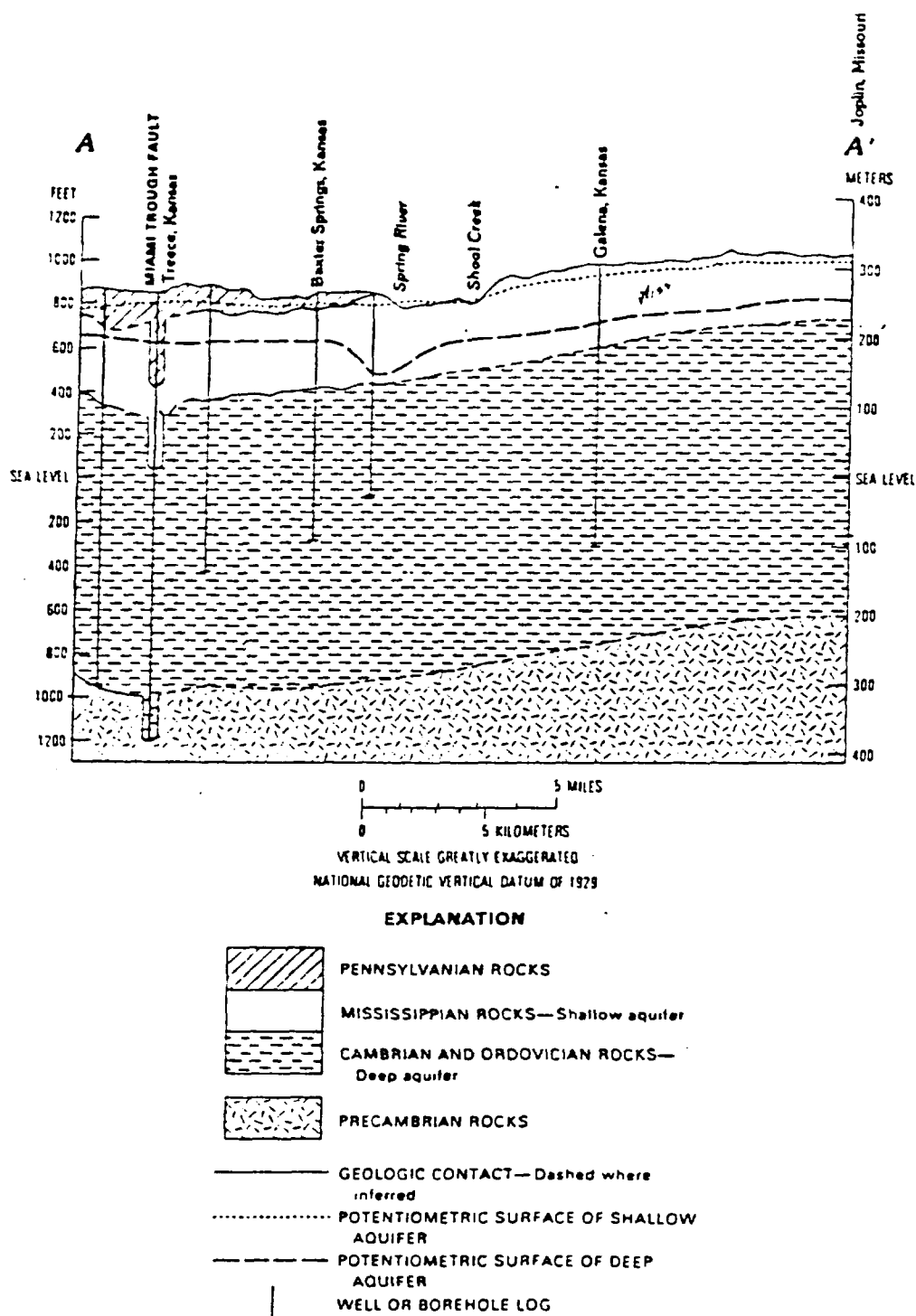


Figure 5 Geologic section from near Treece, Kansas, to Joplin, Missouri. Trace of section shown in figure 2. Potentiometric surfaces based on measured or reported water levels. (after Spruill, 1987)

rocks, caves, sinkholes, and perhaps drainage channels probably formed a karstic topography of considerable relief over which the more terrestrial Pennsylvanian sediments were deposited. Many Pennsylvanian "filled sinks" are collapse structures formed during post-Pennsylvanian time. Calcite was dissolved, leaving layers and fragments of the more resistant chert. Many authors considered the resultant voids, and fractures associated with collapse, as well as with later tectonic stresses associated with the features shown in Figure 2, controlling factors in the migration of the fluids that deposited the ores in brecciated chert. Erosion has removed the largest part of the Pennsylvanian sediments in the study area, allowing circulation of meteoric water under generally unconfined conditions. Several outliers of these Pennsylvanian sediments exist in the general area. They occur as both hilltop caps and as in-fill material within collapsed sinks. Within these collapsed structures free circulation of meteoric water occurred under generally unconfined conditions.

Winslow (1894, p. 596) described the lead and zinc deposits as "in all their natural relations, a part of the Jasper county subdistrict (of the southwestern Missouri mining district);... conditions are to be seen here which are nowhere so well developed within the Missouri line, and which are calculated to throw much light on problems in which we are interested;..." "This camp was first known as the Short Creek mining district, from the name of the small creek flowing just north of the town, westward into Spring river." He reported that "the first

discovery of ore in this district was in 1868 in a well; it attracted but little attention..." "Not until April 1877, was the discovery made by two prospectors, which immediately brought about the opening of the deposits." (p. 597). Siebenthal (1915) included the deposits in the Joplin Field. The Galena field (or camp) was part of what is referred to in the literature as the Tri-State field (Missouri, Kansas, Oklahoma) of the Joplin Region (Siebenthal, 1915).

CHAPTER 3

An Assessment of Premining Surface and Ground Water Chemistry of the Galena, Kansas Area

This chapter provides a review of the premining surface and ground water chemistry in the vicinity of the Galena site along Short Creek. Old surface water data (prior to 1900) proved to be difficult to find for Short Creek. More recent data were obtained from the U.S. Geological Survey Kansas Division at Lawrence, Kansas. These data were used as the base for the modelling studies. Projections as to actual values likely to be found for such parameters as Pb, Zn, and pH are given in the chapter on geochemical comparisons. For ground water in general, some data were obtained from early reports on wells and springs in the area. These reports by Schweitzer (1892) and Bailey (1902) are helpful in determining the premining quality or likely quality of shallow ground water in the Galena area.

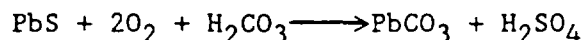
Bailey (1902) makes several comments on water quality. On page 304-306, he reports chemical data on two "iron" springs in the Baxter Springs area. On page 324, we find the comment that Cave and Chico Springs near Galena "...get water from highly fissured limestone and chert formations which produce lead and zinc." Chico Spring (p. 315) near Galena contains a high iron content. We also note the comment (p. 314), "This water contains traces of zinc." It also (table p. 315) contains high levels of iron (2.7 mg/l) and sulfate (65 mg/l) as do springs from the Baxter Springs area (p. 222-224). The presence of iron and sulfate are clear indications of a mobilization and dissolution of key elements from the country rock.

Reports of mineralized ground water can be found in Winslow (1894) and Haworth (1904). These waters very likely were similar or contributed to any spring waters occurring in the area. Data from springs are an important indication of the chemical nature of the shallow ground water present in an area. Springs are usually produced as a result of the intersection of the local water table with the surface. Fed by rain water and having passed through the fissured and fractured rocks and unconsolidated sediments below the soil zone, they have been both affected and acted upon by the shallow subsurface geology of the area through which they have moved. For this reason, we have given careful consideration to the data on springs available in the literature. We refer to them as appropriate in the following pages of this report.

On page 82, Haworth (1904) states, "Cavities from which ore crystals have been dissolved are abundant in places where ground water is now dissolving the ore." This clearly indicates that the ground water had to be charged with lead and zinc. Continuing our discussion from Haworth we find (p. 85), "Along Short Creek Valley limestone and flint are interbedded...the area is filled with ore." Since surface outcrops were known in the area and Short Creek flowed over the surface exposure of a sulfide ore body, it is clear that both the surface and any shallow ground water had to be passing over and through a slightly oxidized ore body. This ore body, given the theoretical considerations reported elsewhere in this report had to be acted upon by the surface waters of the area. It, in turn, had to have

an effect on these waters--likely lowering the pH (possibly to below 6) and leading to a mobilization of lead, zinc, and other elements (e.g. Cd, Fe). The local waters of the Galena site must clearly have been carrying cadmium, zinc, and possibly low concentrations of Pb in solution. Given normal solubility relations, we would expect the lead to drop out of solution first followed by the zinc. The sulfate ion generated by weathering and oxidation reactions on the exposed ore would clearly have been rather high in the surface and ground waters of the area. The chemical analyses of local springs given in Bailey (1902) bears this out. The occurrence of anglesite coatings on rocks of mineralized areas proves that oxidation conditions existed.

Furthermore, as the early geologic reports note, Short Creek flowed across or along the fissured ore body for a distance of approximately one mile. Exposures in and along the creek bed were common with oxidized minerals found in the creek bed. This clearly proves that weathering and oxidation reactions with the original sulfide ore bodies had taken place. Precipitation of the silicate, carbonate, sulfate, and oxide minerals of lead and zinc demands that these ions go through a solution stage thereby providing the means for movement of these ions into any moving waters in the area (ground and surface water). For example, the oxidation reaction of PbS (galena) via any carbonic acid that could be supplied by limestone weathering or decay of natural organic material in the area leads to precipitation of cerussite and production of more sulfuric acid:



Note also that the sulfuric acid produced in this reaction (similar products are produced for ZnS and other sulfide minerals) leads clearly to further acid chemical reactions and a definite reduction of pH ($\text{pH} < 7$) in the containing waters.

Surface Water

Oxidation of sulfides by circulation of oxygenated meteoric (surface water) or shallow ground water through the void spaces and fractures created in the country rock by natural fissures and jointing, as well as leaching of oxidation products by between 40 to 45 inches of annual rainfall would be expected to be a principal cause of higher concentrations of sulfate, heavy metals (zinc, cadmium, and lead), and excessive acidity in surface and shallow ground waters during premining time. A rising and falling of the water table (similar to that indicated in Fig. 5, chap. 2) in the area in the premining era clearly would lead to alternating oxidizing and reducing conditions in the shallow subsurface. Such reactions, under the natural conditions prevailing in the premining era would have led to a mobilization of selected trace elements (Zn, Cd, etc.) in the area with subsequent movement of these surface generated into the regional ground water system.

In brief, a careful review of the appropriate literature on the subject (Winslow, 1894; Bailey, 1902; Haworth, 1904; and Brockie et al., 1968; and others) demonstrates beyond reasonable doubt several facts important to an understanding of the surface and ground water chemistry of the area:

1. Short Creek flowed over and along an exposed sulfide ore body.
2. Weathering and oxidization reactions clearly took place in the presence of the oxygen and carbon dioxide available in the atmosphere and present in circulating surface and shallow ground water of the area.
3. These reactions clearly would have mobilized selected elements (Fe, Pb, Zn, Cd) into solution for varying periods of time depending on the individual solubilities of the respective minerals containing these elements. Note the effect of the sulfide ore body on these elements in the shallow ground waters near the unmined Flambeau sulfide ore body in Wisconsin (Fig. 1; reproduced from May, 1977).
4. These reactions would have acted on the iron sulfide (marcasite or pyrite) plus other sulfides present to generate sulfuric acid and the appropriate oxidized minerals (all reported in the district; Ritchie, 1986).
5. The production of sulfuric acid would have led to an increase in sulfate ion in solution and, more importantly, to a lowering of the pH of both surface and ground water in contact with the ore bodies.
6. The lowered pH would have continued the reactions leading to more mobilization of the elements zinc, lead, cadmium, etc. until the pH was raised downstream by neutralization reactions with the bicarbonate water generated in the streams and ground water systems of the area (see pH curve in Fig. 1) and by the presence of limestone outside the chert zones of the Galena area itself.

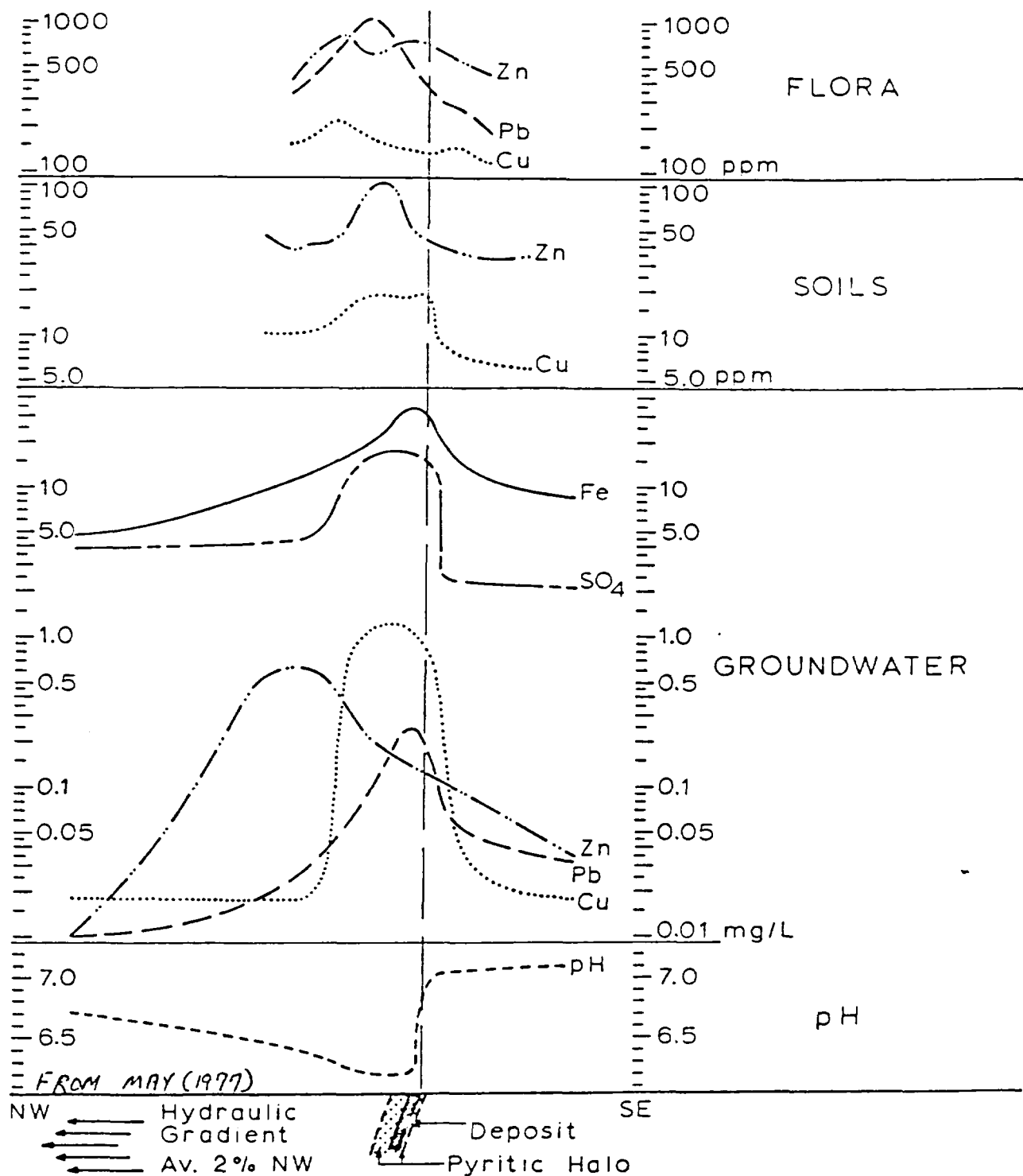


FIGURE 1 : IDEALIZED CROSS SECTION
RELATIONSHIPS BETWEEN FLAMBEAU DEPOSIT
and its
ENVIRONMENT

7. In all cases, the mobilization of these elements and their subsequent movement into the local water system and the attendant lower pH's would have definitely caused a lowering or deterioration of surface and ground water quality in the immediate vicinity of the ore body.

Shallow Ground Water

The purpose of this section is to provide a brief review of information pertaining to the quality of water in the shallow aquifer prior to mining in the vicinity of Short Creek and Galena, Kansas. In the literature, the shallow aquifer generally is equivalent to the Boone formation. Siebenthal (1915, p. 26) included the whole vertical section of Mississippian age rocks from the base of the Chester to the underlying Chattanooga shale in the Boone formation.

Siebenthal, p. 268, mentions that experience in the Joplin region has shown that for the shallow aquifer, the water table in all new mining camps stood nearly at the surface of the ground or not lower than the surface drainage, and everything indicates that it stood so during the period of ore deposition and during premining time. Haworth (1904, pp. 96-101) demonstrates that the principal source of recharge to the shallow aquifer is precipitation falling on the exposed rocks of Mississippian age in the local area. The discharge of water from the shallow aquifer, prior to mining activity, was through pumping of shallow wells, by springs, and by seepage to the streams that drain the area.

In his discussion of springs in the Joplin district, W. S.

Tangier Smith (1905) states that springs are common throughout the district, especially along Shoal Creek and its tributary valleys. He indicates that analysis number 1, shown in Table 1, is probably typical of most springs. Note the indication of trace amounts of lead (Pb).

Of the comparatively few spring waters of the district which differ from those just referred to, one (analysis no. 2 in Smith, 1905) contains sodium sulfate, in addition to calcium bicarbonate. The sulfate values strongly indicate an origin from oxidation of sulfide metals in the absence of local gypsum deposits. A few of the springs of the district contain, in addition to the constituents usually found in such waters, more or less zinc derived from the oxidation of neighboring deposits of zinc ore. This applies particularly to the springs in and near Jackson, Roaring Spring, and Gordon Hollows, most of which contain more or less of a cream-colored to nearly white flocculent deposit. The color of the deposit is likely due to the presence of zinc carbonate (hydrozincite) in suspension in the waters.

All of the waters showing these deposits probably contain zinc, which is known to occur in four of the springs. One near the head of Roaring Springs Hollow, according to an analysis by Mr. W. George Waring, contains 102.8 parts per million, while two springs nearly a mile southeast of the mouth of Gordon Hollow, and just north of Shoal Creek (analysis no. 4 and 5, Smith, 1905) contain respectively 120 and 132 parts per million of zinc. Other springs containing zinc are the Great Western, nearly three

miles north of east of Joplin, and the Green spring east of Empire, which are shown by analyses to contain respectively 35 parts per million and 12.6 parts per million of metallic zinc.

Siebenthal (1915, p. 44) states that the scattered "buttermilk" springs of the district, which carry large quantities of zinc carbonate, mark the outcrop of exclusively cherty strata which may have elsewhere received either mine drainage or drainage from oxidizing sulfide ore bodies that have not been neutralized by contact with limestone. Analysis number 116 in his synoptical table is the same as analysis number 4 in the above table, and analysis number 87 in the synoptical table is number 1 in the table below. Also in the synoptical table, analysis 102 and 109 are for Chico Spring and Cave Spring, both at Galena. The analyses listed below (Table 1) have been calculated from the reacting values (equivalents per million) shown in the synoptical table. Note the report of traces of lead, the concentration of which would be low under any conditions.

Table 1 - Data for Chico and Cave Springs

	Chico Spring (1901) parts per million	Cave Spring (1901) parts per million
Sodium	3.4	2.5
Potassium	--	--
Calcium	46	20
Magnesium	6.8	1.6
Lead	Tr	--
Sulfate	65	34
Chloride	3.5	2.8
Bicarbonate	94	26

Parker, H. N. (1911, p. 64) lists assays of underground waters from Cherokee County. Those assays of springs and shallow wells of interest to this review are shown in the Table 2.

Table 2 - Underground Waters from Cherokee County

No. 1/	Date 1905	Source	Depth (Feet)	Fe*	CO ₃	HCO ₃	SO ₄	Cl
13	July 13	Empire Well	125	Tr	.0	80	119	22
14	do	Empire Well, 2 mi N and 2 mi W of city	20	.0	.0	162	113	65
15	do	Empire, Chico Spring W. of city	--	.0	.0	210	37	22
17	do	Galena, Till- man Spring NE of city	--	.0	.0	133	42	12
19	July 10	Lowell City well	30	.0	.0	299	56	30

1/ Same as number shown on table 11, WSP 273

* Fe Iron
 CO₃ Carbonate
 HCO₃ Bicarbonate
 SO₄ Sulfate
 Cl Chloride

None of the limited number of shallow ground water analyses pre-date mining of lead and zinc in the Galena-Short Creek area of the Tri-state district. However, these few analyses and the descriptions given in the reports do serve as a basis for characterizing the chemical quality of the shallow ground water moving in the area in premining time. The sulfate concentrations are always suggestive of sulfide oxidation occurring through the activity of percolating oxygen and CO₂-charged surface waters.

The analysis of spring number 1 from Smith (1905) compares favorably with the median values given in Feder (1969, p. 33) for springs in the Joplin area and, as Smith indicates, it was typical of water from most springs in the area. The analyses of Chico Spring and Cave Spring from Siebenthal (1915) and the assays of shallow wells and springs from Parker (1911) all show an increase in sulfate content (34-119 ppm) over that found in

Smith's number 1 spring (4.2 ppm). It is related to the oxidation and subsequent leaching of sulfide ores caused either by mining or by leaching of unmined ore bodies (small or large) scattered throughout the unmined subsurface area.

Smith (1905) attributes the large zinc content of springs number 4 and 5 and others mentioned in his text, to the oxidation of neighboring deposits of zinc ore. Siebenthal (1915) attributes the large quantities of zinc carbonate in "buttermilk" springs to either mine drainage or drainage from oxidizing sulfide ore bodies that have not been neutralized by contact with limestone. Thus, it is evident that early authors considered it likely that large amounts of carbonate could occur naturally in ground water. Most of the springs mentioned as containing large amounts of zinc (102-132 ppm) were located in the Shoal Creek basin adjacent to the Short Creek basin. Green Spring (12.6 ppm of zinc) located east of Empire was likely in the Short Creek basin. Spring waters provide an indication of the possible chemistry of the local shallow ground water systems prior to mining.

Haworth (1904, p. 78) states that the largest beds of chert known anywhere in the southwest mining district are found at Galena where a single chert body extends from northern Empire to Shoal Creek, a distance of fully four miles. The width is variable, but is at least three miles in the widest place. The chert areas outlined in his report show them extending up tributary valleys of Short Creek. On pp 102-103, he notes that water in mines with solid flint rock walls remains acid while

that in mines with limestone walls rarely if ever showed acid reactions. Similar reactions were undoubtedly occurring in premining time as surface and shallow ground water flowed over and through the "flint areas" as opposed to the limestone-dominated areas outside of main ore zones.

It is to be expected that these processes were occurring naturally during premining time and that oxidizing shallow ore bodies were contributing free sulfuric acid and soluble metallic sulfates to surface and shallow circulating ground waters. In the specific Galena-Short Creek area, because of the lack of buffering capacity of the chert rocks, these waters likely would have been more acid and contained more zinc in solution than waters in areas of limestone domination.

In closing this section on the premining surface and groundwater chemistry of the Galena area, we need to be reminded that the public attitude toward water quality was different in 1877 than it is today.

A minor but important factor relating to the quality of water and its use has to be the attitude of people using it. To put this into proper perspective, we need to consider the 19th Century view of the general public and especially the medical profession toward mineral waters. Excellent descriptions of this view can be found in the books by Schweitzer (1892) and Bailey (1902). Portions of these comments are given next.

The use of mineral water as a health palliative has been encouraged for millennia. Schweitzer noted that the inscription above the baths of Antonius of Rome states "Curae vacuus hunc

adeas locum ut morborum vacuus abine queas." "Come to this place free from care that you may leave it free from disease."

Mineral waters were used for many purposes in the late 19th Century and were classified according to use. I can only quote from Bailey to make the point. "Waters are divided into three classes (p. 50) as far as their reaction is concerned - namely, neutral, acid, and alkaline." "The system (meaning the body, our addition) is so constructed that it can take care, for a time at least, of an excess of acid or alkaline." "Acids in the stomach (p. 51) assist the action of the pepsin digestion, they also increase the flow of the gastric juice. Acids are very useful in that variety of dyspepsia in which not enough acid is secreted." They go on to note that "The free acids, that are found in waters are sulfuric...derived from oxidation of pyrite (FeS_2). It is clear that the origin of acid was understood.

It is not necessary to quote extensively from either Schweitzer (1892) or Bailey (1902) to show that our view of what is good quality water in the 1980's and what was considered good quality water in the late 19th Century is quite different. They felt that mineralized acidic, alkaline, water etc. each had a therapeutic part to play in the overall health delivery system. In brief what we consider "bad or polluted water" would very definitely not have been so classified before the turn of the century. Waters clearly polluted or bad were recognized as such, but waters carrying certain elements such as Pb, and Zn, and others in the 0.01-10 mg/L range and with a pH in 5-7 range would not likely have been considered bad or even highly polluted waters.

If anyone doubts this then I urge they read pages 30-37 of Schweitzer (1890) and pages 46-67 of Bailey (1902). Bad water or polluted water as we define it today in many localities and under many circumstances clearly did not have the same meaning in the late 19th Century. This attitude still prevails, in part, in the view by some even today that drinking soda water, soaking in certain mud and water baths, etc., has definite (although unproven) therapeutic effects.

The chemical techniques and analyses given in the literature were those appropriate for the time. They are reported in more detail in Schweitzer (1892; chapter II, pages 11-22) and Bailey (1902; chapters V and VI, pages 82-95). Many values considered essential today (e.g. pH, Pb, Zn, Cd, etc.) were not routinely reported 75-100 years ago.

CHAPTER 4

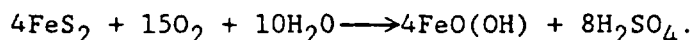
Galena Subsite - Geochemical Comparisons

In order to understand properly the premining geochemistry of the area in the vicinity of the Galena subsite, it is necessary to provide a basic review of the geochemical concepts relative to classic massive and/or sheared sulfide ore bodies. We do this to provide an assessment of premining water quality based on geochemical comparison with similar ore deposits elsewhere. It is not necessary to review in detail the many discussions which are prevalent in the scientific literature relative to the chemical reactions operable in the surface and near surface waters near sulfide ore bodies. All the discussions present essentially the same arguments, as they must, because the basic chemistry is the same in all instances. To avoid duplication, this discussion is restricted primarily to data presented in two classic and basic geochemical texts on the subject: Levinson (1974) and Hawkes and Webb (1962).

In reviewing this data it is necessary to keep in mind that the early geological reports of the area emphasize that extensive sulfide ore bodies and sulfide mineralization occurred in the surface and relatively near surface areas. The deposit at Galena, Kansas and others elsewhere in the tri-state mining district were all sulfide ore bodies. The laws of nature and of the geochemical reactions operating in this area were the same then as those now observed near sulfide ore bodies elsewhere in the world.

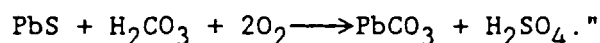
Let us start with the basic premise of the occurrence of a sulfide deposit replete with the key sulfide minerals and large (10-20%) amounts of pyrite (FeS_2) and marcasite, another iron sulfide, dispersed among the ore minerals and country rock. Marcasite is the most common iron sulfide found in the Galena area. These minerals are abundant and widespread in any sulfide ore deposit. All references to the mineralogy of the Galena area contain discussions of the presence, distribution, and abundance of these minerals along with the ore minerals of interest - galena (PbS) and sphalerite (ZnS). The latter mineral commonly carries varying concentrations of cadmium in it, in the Galena site and elsewhere.

Pyrite and marcasite are among the abundant sulfides present (along with ZnS , PbS , CdS , etc.) and they are all easily weathered (or broken down, dissolved) in nature. Basically the weathering of iron sulfides (or other metal sulfides) involves the oxidation of both Fe and S; a simple example is represented here:



Other, successive reactions are possible but they also lead to the production of more H_2SO_4 (sulfuric acid). Different representations of these reactions can be given but the end result is the same. This topic is discussed in considerable detail in Levinson, (1974 p. 75-86). Once formed this acid can lower pH drastically, possibly to 3.0. Levinson (1974, p. 78) states "in this acid environment many other sulfide minerals (e.g. sphalerite) or native elements are attacked and it is this

attack which permits the initial mobilization ...". "Those simple sulfides such as sphalerite and galena, that do not contain iron, may be oxidized directly, or may be dissolved by ferrous sulfate or sulfuric acid. Regardless of the mechanisms, the oxidation of any sulfide mineral leads to the formation of acid solutions..." "The sulfuric acid generated during the oxidation of any metal sulfides may react not only with the sulfide, but also with the carbonate rocks such as limestone." This latter reaction would generate more carbonic acid - which is already present in rain water and groundwater. The generation of H_2CO_3 (carbonic acid) also results from the oxidation or breakdown of any natural organic material (grass, wood, etc.) of any kind present on the surface or in the soil of any area. Continuing our quotations from Levinson, "This acid may also contribute to the oxidation of sulfur in sulfide minerals, for example in the case of galena:



Note that lead carbonate (cerussite) was reported in the ores from the tri-state mineral area (Ritchie, 1986). Note also that the reaction produces more sulfuric acid by which additional solution can take place. It is important to remember that these straight forward common reactions all act to solubilize lead and zinc. Krauskopf (1967) has presented a succinct summary of the end results of the chemical weathering of sulfide minerals by observing that this process "(1) gets the metal ions into solution or into stable insoluble compounds under surface conditions; (2) converts sulfide ion to the sulfate ion, and (3) produces relatively acid solutions." Levinson (1974, p. 79) also

adds, "It is extremely important to realize that chemical weathering of sulfide minerals may completely remove any evidence of mineralization from the surface."

Continuing our review of the basic geochemical processes likely to have been working at the Galena subsite, we turn to another classic text on the subject - that of Hawkes and Webb (1962, pp. 231-40). Referring to the issue of solution - they remark "Fracturing promotes the liberation of soluble metals by increasing the reactive surface between the ore and oxidizing solutions. Water draining highly sheared ores will tend to show stronger anomalies than water from compact...ores." We know from the many geologic reports of the highly fractured and sheared nature of the ore deposits that were present in the Galena subsite (e.g. Brockie et al., 1968). This fact noted by all the early authors should be kept in mind at all times when reviewing the chemistry of the shallow ground waters of the Galena area. The surface was fissured, fracture, jointed, etc. and was therefore extremely porous. This provided an exceptional environment for the type of reactions discussed here to have occurred. Hawkes and Webb (1962) go through an extended discussion of this mobilization process as it applies to ore deposits in geographic settings very similar to those that must have existed at Galena, Kansas in the 1870's.

If we examine related ore deposits on a world wide basis under a host of climatic conditions, we find situations similar to those that must have prevailed at Galena, Kansas prior to mining. Examples from several other regions are illustrative.

These natural reactions are also evident (as expected) in a view of the Draft Environmental Impact Statement for the Red Dog Mine Project of Northwest Alaska. The massive sulfide ore body (Pb, Zn, As, Barite) is located in the DeLong Mountains of Northwest Alaska. All of the area, like the previous study described, is undeveloped. The geography is one of gently sloping hills, broad stream valleys and poorly defined surface relief, in many ways similar to the area of SE Kansas (except for climate). The major drainage in the area, Ikalukrok Creek, is clear with low color levels, and very low suspended solids, etc. except below the confluence with Red Dog Creek. The latter has waters atypical of those Arctic streams in the region because of toxic concentrations of Zn, Pb, and Cd that are mobilized by the waters of Red Dog Creek as it flows over a large highly mineralized sulfide ore body. Table 1 provides an illustration of comparative values between high and low metal concentrations to be expected in waters flowing over and near an ore body. Other locations are compared in Table 2.

Table 1
Red Dog Creek, Alaska--Concentration of Trace Elements (mg/l)*

<u>Red Dog Creek</u>	<u>Highly Degraded</u>	<u>Clean Water</u> (away from ore body)
Zinc	3.0-50.0	0.02-0.05
Lead	0.05-0.5	0.0004-0.01
Cadmium	0.02-0.5	0.001-0.004

*From Fig. IV-7, mg/l = ppm at these concentrations

geologic formation in which the Zinc and Lead ores occur are found as that part of the sub-carboniferous group known as the Keokuk formation. This outcrops on (emphasis mine) Short Creek..." "The Lead and Zinc ores are among the broken limestone and chert. They have been deposited from waters in which they were held in solutions and ..." "The waters coming over these various minerals is more or less charged with them and with silicic and sulfuric acid and as a result the breccia or limestone is again locally porous..." Mudge (p. 578, 1883) also states "the ores... were transported in solution and precipitated elsewhere. The latter processes are doubtless still in operation." In this report of the State Geologist the common minerals mentioned are galena, sphalerite, calamine (now called hemimorphite), and cerussite (an oxidized mineral).

It is clear from the references of those who were on site in 1877 that ore deposits occurred on and along Short Creek (e.g. Haworth, 1904; Mudge, 1879). The ores also were being deposited from solution and most importantly those waters were likely charged with sulfuric acid (H_2SO_4) and hence the pH must have been acidic. Furthermore, they felt the solution process was still in operation, and must have been acted upon by surface waters. It is known that pieces of lead ore, were found in the soil zone of the Short Creek diggings. For this information, we refer to Mudge (1879) in the First Biennial Report of the State Board of Agriculture. In describing the "Short Creek Diggings" he states (p. 82) "the lead ore - galena - is found deposited in three conditions; as float mineral in the loose soil near the

surface... - the first owes its situation to the disappearance, during long geological ages, of the original bedrock..."

In brief then, we know that ore was found on and along Short Creek and was present in the soil and surface rocks of the area.

There exists no way that rain water and surface water flowing over and through the soil and surface rocks cannot have affected the weathering and oxidation of the ores. These chemical reactions are not likely to have been any different here than those we have described for other situations world wide. There can be little doubt that prior to mining the surface water chemistry of Short Creek and the shallow ground systems under and adjacent to the creek was effected by the runoff from these sulfide deposits. The creek water must have been at least slightly acidic (pH less than 7.0) and contained lead and zinc in solution at least to the solubility limits of the minerals in the creek waters at pH's of 6.0-7.0 or possibly less at times.

CHAPTER 5

Computer Simulation of the Pre-Mining Quality of Ground and Surface Water in the Vicinity of Short Creek, Galena, Kansas

Introduction

Waters in regions that have experienced the mining and milling of metals commonly contain elevated concentrations of the metals, as well as exhibiting low values of pH and high concentrations of dissolved sulfate. It is of interest here to attempt to go back in time and to determine what the natural concentrations of metals and other dissolved components may have been in the waters of the region prior to the initiation of mining. In other words, it may be important to attempt to reconstruct the natural background concentrations of dissolved species in the waters.

Unfortunately, it is always difficult and sometimes impossible to determine such natural background concentrations after the disturbances associated with mining and milling tend to uncover and expose metalliferous rocks and minerals of the region to natural processes of weathering and erosion. Elevated concentrations of metals and associated elements, such as sulfur, may therefore be imposed on the waters of the region as a result of the mining and milling processes. On the other hand, mineralized areas in which mining has occurred are, by definition, enriched in the valuable metals. Elevated concentrations of those metals and associated elements therefore occur naturally in the surface and ground waters of the region; this forms the basis for geochemical exploration for hidden ore

bodies using the chemistry of natural waters (Rose and others, 1979).

The area near Galena, Kansas, experienced years of mining and milling activity by many individuals and companies (Brockie and others, 1968). There can be little doubt that these past activities have released metals and associated elements to the surface and shallow ground waters of the region. However, it is also highly probable that the natural waters of the region also contained elevated concentrations of the elements of concern, even before the first mine was opened, simply because of the presence of extensive ore bodies in the bedrock of the region. As mentioned earlier, it is difficult to separate the chemical effects of mining and milling from the natural background concentrations in a mineralized region. However, the advent of geochemical modeling offers a new and powerful method for "going back in time" to determine, or at least to approximate, the chemical compositions of natural waters that should have existed in a mineralized region before the initiation of mining.

Geochemical Modeling of Natural Waters

The approach taken in this study is to use a geochemical computer model to predict the concentrations of metals and associated elements that should have been present in surface and shallow ground waters of the Tri-State Mining District (Missouri, Kansas, Oklahoma) prior to the beginning of mining. Specifically, the geochemical model computes the concentrations of chemical elements that should have dissolved into the natural waters that were in contact with the ore and gangue minerals of the mining district. In this report particular emphasis is placed on the waters of Short Creek and the shallow-ground water system near Galena, Kansas.

The Computer Model PHREEQE

The model used in the simulations is PHREEQE (an acronym which is pronounced "freak" and which stands for "pH-redox-equilibrium-equations"). The model was developed by personnel of the U.S. Geological Survey (Parkhurst and others, 1980). It was chosen for this study for four main reasons. First, PHREEQE has been widely used and thoroughly tested by a number of individual researchers and agencies (see, for example, the study of PHREEQE conducted for the U.S. Department of Energy by Intera Environmental Consultants, 1983). Second, PHREEQE is rapidly becoming a standard working tool for hydrogeologists and geochemists, as exemplified by its use by the U.S. Geological Survey in a study of a regional aquifer system in the northern Great Plains (Henderson, 1985). Third, one of the options available in PHREEQE is the ability to determine the composition

of a water which has equilibrated with one or more minerals of interest; in this usage PHREEQE differs from several other geochemical computer models which do not allow such equilibration to be modeled. And fourth, the thermodynamic database contained within PHREEQE is large and appropriate for modeling the waters of the Tri-State District.

Assumptions Involved in the Modeling

- (1) The minerals of the district and the natural waters were in contact for sufficiently long periods of time prior to mining to allow a close approach to chemical equilibrium.
- (2) The minerals and dissolved species contained within the PHREEQE database are realistic and adequate to model the natural conditions.
- (3) The thermodynamic data that comprise the PHREEQE data base are accurate.

I believe that each of the three assumptions above is conservative and justified. With regard to the first assumption, it is very likely that the ground waters of the district would have been in contact with minerals of the ore bodies and wallrock for many years prior to mining. This amount of time would have been adequate for a close approach to equilibrium for most of the minerals described by PHREEQE. With regard to surface waters, contact times might have ranged from hours to days, which would generally not be adequate for a close approach to equilibrium, except in those instances in which the streams were fed wholly or in part by ground water. For the surface waters, the computed predictions of the dissolved concentrations of the metals and

associated elements should generally be viewed as maximum theoretical values. We note this because of the possibility of shallow ground water recharge by surface water moving through the fissured ground present in the area. During low flow conditions, it is likely that the major part of recharge to Short Creek was from the ground water system. This point needs to be kept in mind while reviewing the material on modelling presented in this chapter.

The second assumption, that of adequate representation of the natural minerals, is quite good. PHREEQE was designed to simulate natural water-rock interactions; as such, it contains a broad and realistic representation of most common ore and gangue minerals. The principal weakness in the PHREEQE database is the absence of thermodynamic data for mineral solid-solutions; that is, most of the minerals are represented as pure end-member phases, such as pure ZnS, pure CdS, and so on. Although it would be more realistic to have solid-solution minerals represented within the database, the conclusions derived from modeling with pure end-members will not be significantly in error for the major chemical components. It is possible that minor components in mineral solid-solutions, such as Cd present in small amounts in ZnS, will not be accurately represented by the pure end-member components (CdS and ZnS) in the PHREEQE database; for such components, the output from PHREEQE must be viewed with some caution.

The third assumption, that of accurate thermodynamic data, is common to all geochemical computer and, in fact, to most of

geochemistry. There is no doubt that some of the thermodynamic data in PHREEQE could be in error. However, the database in the present version of PHREEQE has been chosen by various researchers over a period of years and is under constant revision; it is essentially the same database as is used in the model MINTEQ from Battelle Pacific Northwest Laboratories (Felmy and others, 1983). Based on various comparisons with laboratory experiments and field observations, the accuracy of the thermodynamic database seems to be quite good for most of the common ore and gangue minerals. For purposes of this study it was necessary to add data for the mineral hydrozincite ($\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$) from an outside source (Sangameshwar and Barnes, 1983).

Input Parameters for Modeling

As implemented in this study, PHREEQE required initial input values for temperature, composition of the initial water, pH (a measure of acidity and alkalinity), Eh (a measure of the oxidation/reduction status of the system), the partial pressure of carbon dioxide gas, and the selection of minerals with which the water was to equilibrate.

Temperature was assumed to be constant at 25°C; deviations of 10°C or so from this value would introduce no significant error. The initial waters were assumed to be pure water or were based on chemical analyses of actual waters in the area of Galena, Kansas. For pure water the initial pH was taken to be 7.0, whereas for natural springs and streams either a field-measured pH or an estimated pH was used. The oxidation-reduction parameter (Eh) was estimated from Figure 1; this was done by

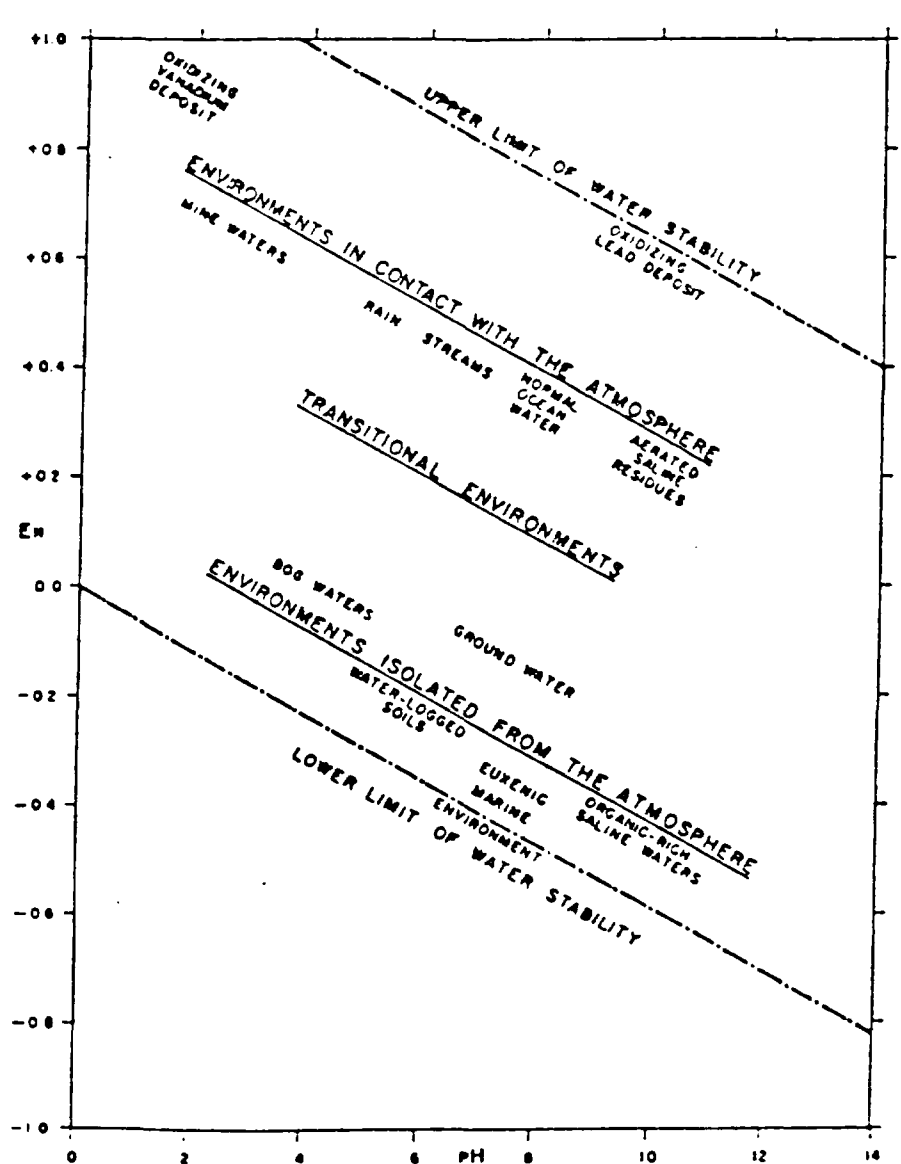


FIG. 1. Approximate position of some natural environments as characterized by Eh and pH. After Garrels and Christ, 1965.

choosing Eh values corresponding to the measured (or estimated) pH values for the various environments shown on Figure 1. The partial pressure of carbon dioxide gas was chosen to be near $10^{-3.5}$ atmospheres for surface waters and from $10^{-2.5}$ to $10^{-0.5}$ atmospheres for subsurface waters. The mineral assemblages were selected from descriptions of the Tri-State ore deposits (Brockie and others, 1968). Initial conditions and parameters are summarized in Table 1.

As noted earlier, the choice of the input Eh values in Table 1 is based on Figure 1, using either a measured or an estimated pH value and then selecting one or more of the environments illustrated in Figure 1. For example, the Eh value of +.403 volts, at a pH of 7.5, given in Table 1 for Short Creek represents one of the "Environments in contact with the atmosphere" shown in Figure 1. Similarly, the zero and negative values of Eh listed in Table 1 correspond to moderately-reducing shallow ground waters or strongly-reducing deep ground waters; the latter choice can be justified on the basis of reports of hydrogen sulfide gas in some of the springs of the region (Haworth, 1904) and by similar reports of H_2S in shallow ground waters of the area (Macfarlane and Hathaway, 1987).

The values of the log of partial pressure of carbon dioxide gas listed in Table 1 are estimates based on published analyses of subsurface waters and soils. The partial pressure of carbon dioxide gas in the atmosphere is $10^{-3.5}$ (0.0003) atmospheres, whereas in subsurface environments the partial pressure may be as high as $10^{-0.5}$ (0.3) atmospheres (see for example, Lindsay, 1979, p. 84).

Table 1. Initial starting conditions used in various runs of the PHREEQE predictive geochemical model. Temperature constant at 25°C. Not all of the minerals were used in any single simulation. The combinations of various starting waters, parameters, and minerals resulted in about 100 individual computer simulations.

Initial water or assumed environment	Initial pH	log of P _{CO2} (atm.)	Eh(volts)	Minerals
pure water, used as shallow and deep sub- surface water.	7.0	-2.5, -1.5	-0.148, -0.177 -0.236	CaCO ₃ (calcite) NiS (millerite) CdS (greenockite) ZnS (sphalerite) PbS (galena) FeS ₂ (pyrite) CaMg(CO ₃) ₂ (dolomite) Fe(OH) ₃ (ferrihydrite)
East Short Creek, used as surface water and ground water.	7.5	-3.0, -2.5 -2.0, -1.5 -1.0, -0.5	+0.403, -0.118 -0.148, -0.207	CaCO ₃ (calcite) NiS (millerite) CdS (greenockite) ZnS (sphalerite) PbS (galena) FeS ₂ (pyrite) CaMg(CO ₃) ₂ (dolomite) Zn(OH) ₂ (precipitate) Ni(OH) ₂ (precipitate) MnOOH (manganite) SiO ₂ (chalcedony) BaSO ₄ (barite) PbCO ₃ (cerussite) CdCO ₃ (otavite) KFe ₃ (SO ₄) ₂ (OH) ₆ (jarosite)
Chico Spring 1 mile NW of Galena, Kansas	4.0 (est.) 6.0 (est.)	-2.0 -2.0 -3.5	0.000 -0.100 -0.100	Zn ₅ (OH) ₆ (CO ₃) ₂ (hydrozincite)

Non-unique Solutions to Modeled Scenarios

It is important to know that the predicted compositions of waters resulting from the various chemical scenarios that were modeled in this study do not represent single, unique answers to the questions that are posed. That is to say, a different combination of minerals, Eh, pH, and partial pressure of carbon dioxide gas might yield exactly the same predicted final composition of the water at equilibrium. The only way to arrive at an acceptable set of parameters and final predictions is to use the best information available on the problem at hand, tempered with a large dose of geological and geochemical "horse sense."

Compositions of Starting Waters

As discussed in an earlier section, the geochemical modeling effort consists of equilibrating a given starting water with an assemblage of minerals, at various initial fixed values of pH, Eh, and partial pressure of CO₂ gas. The starting waters that were chosen were: (1) pure water, (2) Short Creek water, east of Galena, Kansas, and (3) water from Chico Spring, one mile northwest of Galena. The pure water was chosen as an analog of rain water, to determine what final composition would result from the equilibration of rain water with various assemblages of minerals.

The pH of 7 chosen for rain water is admittedly higher than natural. It was a conservative choice of pH. If mobilization could be demonstrated with this pH then lower pH's (more acidic) would certainly have mobilized and put into solution higher

concentrations of lead, zinc, and cadmium. As is demonstrated by these computer simulations, concentrated ions of these metals would certainly have been put into solution at levels demonstrated to have occurred elsewhere. If we then note that surface water in equilibrium with atmospheric CO_2 has a pH near 5.7, it should then be obvious that high concentrations of Pb, Zn, and Cd, could easily have been present in Short Creek and the shallow ground water system in the fissured, chert-rich limestone poor, mineralized zones near Galena, Kansas. The key point to keep in mind is that without extensive limestone present, neutralization of the naturally acidic waters would be delayed until the moving water had left the chert-rich areas.

Water No. 2, from Short Creek east of Galena, was selected to compare with water in Short Creek west of Galena, after model equilibration with various assemblages of minerals. The spring waters (Nos. 3 and 4 above) were modeled to determine the states of saturation of the waters with respect to hydrozincite ($\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$); this is of interest because some of the springs in the region are reported to precipitate hydrozincite as they exit from the ground; these are locally called "buttermilk springs."

The starting compositions of the waters used in the modeling are listed in Tables 2 and 3. The analyses of Short Creek and Chico Spring were taken from the published literature (Bailey, 1904) and provided to the writer by Dr. Ernest E. Angino.

In the modeling effort, the waters in Tables 2 and 3 were equilibrated with various assemblages of the minerals and under

Table 2. Published analyses of the waters used as starting materials in this study. Major dissolved components only. See minor components in Table 3. The pH values for the spring waters are estimated from the difference between the milliequivalents per liter of reported positive species and the milliequivalents per liter of reported negative species; see text for discussion..

Water Source	concentrations, in mg/L										pH
	Na	K	Ca	Mg	alkal (CaCO ₃)	HCO ₃	Cl	SO ₄	SiO ₂		
pure water, to simulate rain water.	0	0	0	0	0	0	0	0	0	7.0	
Short Cr., 2 miles east of Galena, KS. Aug 12, 1981.	5.1	2.0	41	4.5	76		2.0	50	6.0	7.5	
Chico Spring, one mile n.w. of Galena, KS	0	0	46	8.6		115	3.5	65	14	4.0	

Table 3. Published concentrations of minor components in waters used as starting materials in computer modeling.

Water source	concentrations, in mg/L								total
	Ba	Cd	Cu	Cr	Fe	Pb	Mn	Zn	As
Short Cr., 2 miles east of Galena, KS Aug. 12, 1981.	0.10	0	0	0	0.02	0	0.04	0.19	0

the conditions listed in Table 1 and the accompanying discussion.

Results and Discussion

Pure Water, in Contact with Sulfide Minerals

The starting point of the modeling effort was to select various assemblages of minerals that were meaningful and consistent with assemblages reported from the Tri-State District. These were taken chiefly from Brockie and others (1968, p. 416). Minerals which were considered include galena (PbS), sphalerite (ZnS), pyrite (FeS_2), chalcedony (SiO_2), calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), millerite (NiS), greenockite (CdS), jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$), cerussite (PbCO_3), barite (BaSO_4), gypsum (CaSO_4), anglesite (PbSO_4), smithsonite (ZnCO_3), and ferrihydrite ($\text{Fe}(\text{OH})_3$). Other minerals and solid compounds that were considered, although not reported by Brockie and others (1968) as occurring in the district, include otavite (CdCO_3), manganite (MnOOH), precipitated $\text{Ni}(\text{OH})_2$, and precipitated $\text{Zn}(\text{OH})_2$. Based upon the geology and geochemistry of the area, it would not be surprising to find these latter compounds in association with the ore deposits. The minerals and compounds which were retained in the final simulations are listed in Table 1.

Strongly Reducing Conditions

To simulate the chemical conditions of deeper ground water in an undisturbed deposit of primary sulfide minerals, an assemblage of calcite, dolomite, millerite, greenockite, sphalerite, galena, and pyrite was equilibrated with pure water at an Eh of (-)0.236 volts. As seen in Figure 1, an Eh of (-) 0.236 volts represents

a strongly reducing condition, as might be expected to occur in a sulfide ore deposit deeply buried beneath the surface of the earth. A partial pressure of carbon dioxide gas of $10^{-1.5}$ (0.03) atmospheres was chosen, which is also reasonable for deep ground waters. The concentrations of dissolved Zn, Pb, Fe, Ni, and Cd in the resulting water were all extremely low, with Ni being the highest at approximately 0.01 mg/L. The water was predominately a Ca-HCO₃ solution, with a final pH of 7.1. The water contained a 63 mg/L Ca, 360 mg/L HCO₃, 34 mg/L Mg, and slightly less than 0.02 mg/L SO₄. Clearly, from these results one concludes that a deeper-buried sulfide ore deposit, within a carbonate-rich wallrock, does not pose any hazard to ground water. This approach is provided as a comparison to what occurs as conditions change as one approaches the surface or moves into an area of increasing oxidation tendency.

Onset of Oxidation

As the cover above the hypothetical ore deposit is eroded and the sulfide minerals are exposed to slightly more oxidizing conditions, the solubilities of the heavy metals increase rapidly. For example, at an Eh of (-)0.207 volts, which is still quite strongly reducing (see Figure 1), dissolved Ni has already risen to a concentration of 0.14 mg/L and dissolved SO₄, derived from the oxidation of millerite, is now at a concentration of 0.24 mg/L. The pH of the water remains at 7.1, with all of the other heavy metals present in concentrations far below detection limits.

As oxidation becomes a little more significant, at an Eh of

(-) 0.177 volts, dissolved Ni rises to 13 mg/L and Fe is now detectable at 0.02 mg/L. The pH has fallen slightly to 7.09 and dissolved SO_4 has a concentration of 22 mg/L.

At an Eh of (-)0.148 volts, which would still be considered to be reducing, dissolved Ni has reached 410 mg/L, Fe is at 9.7 mg/L, and Zn at 0.02 mg/L. The pH has fallen to 6.9 and dissolved SO_4 , chiefly from millerite, pyrite, and sphalerite, exceeds 700 mg/L. These results indicate that significant contamination of ground water can occur as a result of exposure of sulfide minerals to very mild oxidation; such conditions could easily occur in nature, even in the complete absence of mining activity.

At this stage in a geochemical simulation, it is useful to ask whether or not other minerals might precipitate to remove some of the metals that have been released from the oxidizing sulfides. This does not seem to be the case for Ni, but Fe could reprecipitate as amorphous $\text{Fe}(\text{OH})_3$. If this were to occur, still at an Eh of (-)0.148 volts, the solubility of Fe would be greatly increased, to 19,140 mg/L. Sulfate would also go up dramatically, to nearly 33,000 mg/L. This dramatic increase in the predicted solubility of Fe results from the destabilization of pyrite due to the presence of $\text{Fe}(\text{OH})_3$. Again, it must be pointed out that an Eh of (-)0.148 volts is well within the range of geological environments that would normally be considered to be oxygen-poor (see Figure 1). Millerite (NiS) was not included in this simulation due to its enormous solubility; however, 0.02 mg/L dissolved Pb is now released by galena and 2.3 mg/L of Zn

comes from sphalerite. Cadmium remains low (0.0003), but this value is probably a minimum figure because it is based on the presence of pure CdS instead of Cd in solid-solution in sphalerite. These conditions are likely to have been encountered in the shallow ground water system present in the area in premining time. Clearly mobilization of trace elements could have occurred.

The main conclusion to be reached from the simulation of the oxidation of a sulfide ore body is that the sulfides are extremely unstable, even under mildly oxidizing conditions. Surface and shallow ground waters that might come in contact with an oxidizing sulfide ore body would therefore be subject to severe natural contamination. Of course, as noted earlier, the computer simulations assume that equilibrium is attained between the minerals and the adjacent waters. It seems unlikely that rapidly flowing surface streams would have adequate time to equilibrate with an oxidizing ore body, even if the ore body were exposed in the stream channel. However, slowly moving shallow ground waters would probably remain in contact with the sulfides for long enough periods of time for severe natural contamination to develop and occur. Under more strongly oxidizing conditions, even more metals may be put into solution. We have chosen a conservative approach to illustrate the level of mobilization that can occur.

The Chemistry of Short Creek

Short Creek flows from east to west through the town of Galena, Kansas. Based on chemical analyses obtained by the U.S. Geological Survey on August 12, 1981, the water in Short Creek east of Galena is alkaline and relatively free of dissolved metals, whereas west of town the pH has become acidic and the water contains significantly higher concentrations of dissolved Cd, Cu, Fe, Mn, and Zn (data were not available for Ni). I have used computer simulations to determine if it is possible for the increases which are observed in the concentrations of the metals in Short Creek to occur as a result of contact between shallow ground waters and assemblages of either the primary sulfides or the secondary oxidation products of the primary ores, under conditions which would be reasonable for the natural field environment.

First, referring back to the preceding section on the incipient oxidation of primary sulfides, it is clear that enormous concentrations of dissolved metals could be produced in waters that are in contact with primary sulfides under strongly oxidizing conditions, such as those that prevail at the surface of the earth (an Eh of approximately (+)0.8 volts at a pH of 7; see Figure 1). In fact, the computed solubilities of the primary sulfides are so high under strongly oxidizing conditions that the PHREEQE model is unable to converge on a correct numerical answer. Therefore, the remaining question is whether or not significant natural contamination could result from contact between surface or ground waters and the natural products of

oxidation of sulfide ore bodies that might have been present at or near the surface of the district prior to the onset of mining. It is known that in some parts of the Tri-State District the ore bodies were originally discovered in surface outcrops and near surface deposits (Haworth, 1902; Winslow, 1894; Broadhead, 1874; and other early reports on area).

Interaction Between Short Creek Water and Oxidized Minerals

The starting composition of water from Short Creek east of Galena, Kansas, is given in Tables 2 and 3. The composition of Short Creek water about two miles west of Galena is given in Tables 4 and 5, from samples collected on the same day (August 12, 1981) as those in Tables 2 and 3.

In these simulations, three different mineral assemblages were chosen to approximate assemblages that might reasonably be expected to develop under various intensities of oxidation of an original sulfide ore deposit. These are listed in Table 6. The second and third assemblages in the table include carbonate minerals of Mn and Cd that are not reported by Brockie and others (1968) from the Tri-State District. However, it seems reasonable that such carbonates could occur, either as primary minerals or as intermediates in the weathering process. The Eh values and partial pressures of carbon dioxide gas in Table 6 are reasonable estimates of field conditions. Note that the Eh value in the first column of Table 6 is highly oxidizing.

As was the case earlier in this discussion, the products of the simulations are the compositions of the waters after equilibration with the mineral assemblages of Table 6. In this

Table 4. Published analysis of the Short Creek water from a location two miles west of Galena, Kansas. Major dissolved components only. See minor components in Table 5.

Date of sample	concentrations, in mg/L								
	Na	K	Ca	Mg	alkal(CaCO ₃)	Cl	SO ₄	SiO ₂	pH
Aug 12, 1981.	9.3	5.0	71	6.5	8	9.0	240	17	

Table 5. Published concentrations of minor dissolved components in Short Creek waters two miles west of Galena, Kansas.

Date of sample	concentrations, in mg/L								total
	Ba	Cd	Cu	Cr	Fe	Pb	Mn	Zn	As
Aug. 12, 1981.	0	0.17	0.020	0	0.010	0	1.7	25	0

Table 6. Three assemblages of minerals and solid compounds used to simulate various degrees of oxidation of a Tri-State ore body.

Highly oxidized (sulfates, hydrox- ides, carbonates)	Slightly oxidized (sulfides, carbonates, sulfates)	Slightly oxidized (carbonate assemblage)
barite (BaSO_4)	barite	barite
jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$)	greenockite (CdS)	otavite
otavite (CdCO_3)	sphalerite (ZnS)	siderite (FeCO_3)
cerussite (PbCO_3)	galena (PbS)	smithsonite
manganite (MnOOH)	cerussite	(ZnCO_3)
ferrihydrite ($\text{Fe}(\text{OH})_3$)	rhodochrosite (MnCO_3)	cerussite
$\text{Ni}(\text{OH})_2$ (precipitate)	calcite (CaCO_3)	calcite
$\text{Zn}(\text{OH})_2$ (precipitate)		dolomite
		($\text{CaMg}(\text{CO}_3)_2$)
$E_h = (+)0.403$ volts	$(-)0.118$ volts	$(-)0.148$ volts
$\log P_{\text{CO}_2} = (-) 3.0$	$(-) 2.0$	$(-) 0.5$

case the starting water was simulated from the analyses of Short Creek east of the town of Galena (Tables 2 and 3). The goal of the simulations is not necessarily to exactly match the observed composition of water from western Short Creek, but instead to determine if it is possible to release meaningful concentrations of dissolved metals and other species into Short Creek water under reasonable scenarios of natural weathering and dissolution.

Table 7 summarizes the results of the PHREEQE simulations, corresponding to the three assemblages of Table 6.

Conclusion

In examining and comparing the results of the three simulations summarized in Table 7, it is important to keep in mind that the purpose of the modeling is to determine if the predicted concentrations of metals and associated species are meaningful from the point of view of establishing natural background concentrations in the absence of mining and milling. It is not the purpose of the simulations to match the observed concentrations in Short Creek west of Galena. With this in mind, it is obvious from Table 7 that high concentrations of dissolved metals and other components can indeed be produced in water from eastern Short Creek by means of natural weathering and dissolution under conditions that reasonably simulate nature. It is not necessary to call upon contamination from man-made sources to explain the concentrations of dissolved species presently found in western Short Creek. Reference to Table 2 shows that the dissolved values of Pb, Zn, and Cd in small streams and shallow ground water in unmined mineralized areas are essentially

Table 7. Columns 2 through 4 correspond to the three columns of Table 6 and represent the compositions of waters resulting from equilibration between the mineral assemblages of Table 6 and water from Short Creek east of Galena, Kansas. Column 5 summarizes the composition of Short Creek west of Galena. Dissolved components only. Concentrations rounded to two significant figures.

	Highly oxidized	Slightly oxidized	Slightly oxidized	Short Creek west of Galena, KS
concentrations, in mg/L except for pH				
final pH	7.2	7.0	6.3	6.0
Ba	0.0092	0.0059	0.20	0
Ca	41	750	210	71
Cd	0.028	0.010	1.2	0.17
Fe	0.00077	0.020	2.4	0.010
K	100	2.0 (not simulated)	2.0 (not simulated)	5.0
Mg	4.5 (not simulated)	4.5 (not simulated)	23	6.5
Ni	49.	(not simulated)		(not reported)
Pb	0.57	0.45	0.45	0
SO ₄	540	1900	50	240
Zn	180	104	18	25

the same as those reported for the shallow ground water and Short Creek in the Galena, Kansas area.

The simulation for Chico Spring is given in the following section. Again reference to Table Z will show that the computed values are in line with what could be expected in shallow ground water in the presence of a sulfide mineral ore body.

The Chemistry of Chico Spring

The chemical composition of Chico Spring is summarized in Table 2. This spring was selected for modeling because other springs in the region precipitate solid hydrozincite when they emerge from the ground. It was of interest to determine the natural concentrations of dissolved zinc that would have to be present in the spring waters if they were at equilibrium with hydrozincite. For this purpose thermodynamic data for hydrozincite was added to the PHREEQE database, and initial input parameters of pH, Eh, and partial pressure of carbon dioxide gas were selected, as summarized in Table 1. A second objective was to determine the approximate concentrations of Cd, Pb, As, Zn, and Ni that could remain in solution without precipitation of a solid compound or mineral. Chico Spring was chosen for this second exercise because it is located very close to the town of Galena and appears to be rather typical in composition.

A word of explanation is required with regard to the initial input parameters listed in Table 1. The pH values were not given in the original old analyses. To arrive at the estimates shown in Table 1, the electrical balance between cations and anions, in milliequivalents per liter, were calculated and in each of the

seven spring waters examined, there was an excess of negative charge. The missing milliequivalents of positive charge were then assigned to hydrogen ion and the resulting pH values calculated that would be required to reach perfect charge balance, thus resulting in the estimates shown in Table 1. Although this is admittedly a highly imperfect approach, it is interesting and perhaps significant that all seven of the spring waters require an acidic pH to balance electrically.

The partial pressures of carbon dioxide and the range of Eh values shown in Table 1 for the springs bracket the values that might be expected for deeper ground waters and near-surface ground waters.

Precipitation of Hydrozincite

The water from Chico Spring, when forced to be at equilibrium with hydrozincite over the range of Eh, pH, and partial pressures of carbon dioxide gas shown in Table 1 yields concentrations of dissolved zinc of from 1.3 to 84 mg/L. In each case the final pH is higher than the initial values shown in Table 1, ranging from 6.9 to 8.4. The highest values of dissolved zinc occur when the final equilibrium pH turns out to be relatively low and the partial pressure of carbon dioxide gas is fixed at the higher value of $10^{-2.0}$ (0.01) atmospheres.

From these simulations, it is obvious that spring waters in the Tri-State District, if they are capable of precipitating solid hydrozincite, are also capable of carrying naturally high concentrations of total dissolved zinc. The natural concentrations of zinc that are predicted by PHREEQE to occur in

equilibrium with hydrozincite are at least as high as concentrations that might otherwise mistakenly be attributed to contamination caused by mining and milling.

Maximum Dissolved Concentrations

Using the composition of Chico Spring as a starting solution, arbitrary concentrations of Cd, Pb, As, Zn, and Ni were added to the water. A predicted list of solid precipitates was then examined, and the added concentrations of the elements were adjusted upward or downward until the water was essentially at equilibrium with the least soluble solid compound or mineral. In this way it was possible to determine the highest concentrations of Cd, Pb, As, Zn, and Ni that could be present at equilibrium in Chico Spring water. This was done for two partial pressures of carbon dioxide gas, $10^{-3.5}$ (0.0003) and $10^{-2.0}$ (0.01) atmospheres, roughly corresponding to near-surface and deeper subsurface conditions.

It was found that at partial pressure of CO_2 gas of $10^{-3.5}$ (0.0003) atmospheres the maximum equilibrium concentrations of the metals would be approximately as follow: Cd = 0.001 mg/L, Pb = 0.1 mg/L, Ni = 0.1 mg/L, As > 10 mg/L, and Zn = 0.1 to 1.0 mg/L. At a partial pressure of CO_2 of $10^{-2.0}$ (0.01) atmospheres the maximum permissible concentrations increase, with the approximate values being as follows: Cd = 0.005 mg/L, Pb = 0.3 mg/L, Ni = 5 mg/L, As > mg/L, and Zn = 1 to 10 mg/L. The values are approximate because it is not certain which minerals or solid compounds should be chosen as the most likely to form from solution; this is particularly the case of Zn, in which ZnCO_3 ,

ZnSiO_3 , and willemite (Zn_2SiO_4) are possible initial precipitates. In the case of As, the PHREEQE database contains only 10 minerals and compounds, so conclusions regarding the solubility of As are rather weak.

Summary and Conclusions

From a series of computer simulations, using reasonable values for input parameters and mineral assemblages, it is clear that natural processes of weathering and erosion in the Tri-State Mining District would be capable of producing concentrations of dissolved metals and associated elements that are very high, in the hundreds or thousands of milligrams per liter. In the absence of these computer simulations, such high concentrations would probably be attributed, perhaps mistakenly, to the effects of mining and milling. This is not to say that mining and milling do not also produce high dissolved concentrations of the elements of concern, but the impact of such activities should be judged only with a full realization that natural processes of weathering and erosion can also cause significant contamination and degradation of natural waters in a mineralized region, especially as sulfide ore bodies are subjected to the oxidation by surface waters or shallow ground waters.

A great many assumptions and simplifications are necessarily involved in applying geochemical computer modelling to the problem of establishing meaningful natural background concentrations of dissolved elements in the waters of a region. Care and judgment are required to make the simulations as realistic as possible. However, when the predictions are

consistent over a wide range of input parameters and initial assumptions, one is certainly justified in utilizing the predictions for the purpose of judging the effect that the activities of man have had on the natural background. It is far more realistic to use the computer-generated concentrations of dissolved species as a measure of natural background than to assume that the waters of a mineralized region were completely pure and free of contaminants prior to the beginning of mining and milling.

CHAPTER 6

Summary and Conclusions

From a review of the historical literature and the supporting documentation, assessments, and determinations made in this report, several conclusions can be clearly stated.

The premining geology of the Galena area most certainly included an exposed oxidizing sulfide ore body, an ore body exposed at the surface and in the shallow subsurface to the effects of oxygen containing waters. Ores and pieces of ore (e.g. galena) were present in the soil zone and immediately beneath it.

The presence of the carbonate, sulfate, and silicate species of the ore minerals of lead and especially zinc are definitive proof of a previous attack on the primary sulfide ore body by oxygen-bearing waters--both surface and subsurface. Similarly the reported presence of Zn in springs in the general area (e.g. "buttermilk springs") supports the premise of oxygenated water attacking the primary sulfide ore body and moving the resulting zinc containing waters some distance. These waters were in fact a part of the shallow ground water systems of the area.

Reprecipitation of appropriate lead, zinc, and other minerals on other lead and zinc minerals as reported in descriptions of minerals found in the area is also indication of the shallow ground water system's carrying capacity, under certain conditions for ionic zinc, lead, cadmium, nickel, iron, etc. The high values of sulfate ion reported in the early spring water analyses from this area (Bailey, 1902) points to oxidation of the sulfide ore body and mobilization of the sulfur as

sulfate.

These findings are in agreement with the predicted capacity of these waters to carry appropriate ions in solution in the area under chemical conditions expected to be present in the vicinity of a weathering sulfide ore body. Comparison with other, similar ore bodies demonstrates clearly the natural ability of stream waters and ground water under pH conditions expected near a sulfide ore body to mobilize levels of lead, zinc, and cadmium now deemed to be undesirable.

Normal weathering and chemical attack of sulfide ore bodies in nature under a wide variation of climatic regimes--from polar to tropical--all produce the same results in streams and ground water near the ore body: a lowering of pH in all surrounding waters, especially those beneath the ore body and those that flow over or along the ore body. This action is followed by a mobilization (i.e. rendering soluble) of the elements of appropriate sulfide minerals found in the ore body. For example, zinc is put into solution from the mineral sphalerite (ZnS) and lead from galena (PbS). Our review of literature on other sulfide ore bodies around the world shows this to be true in all cases. The levels of trace element mobilization, in fact, are not greatly different at Galena, Kansas, when compared to data reported for other mineralized area.

In all probability, this same mobilization process was active on exposed and shallow ore bodies along Short Creek at Galena, Kansas in premining time.

It is known that the largest areas of chert occurrence, fractured or otherwise, are found in the Galena, Kansas area.

These are essentially limestone-free areas and hence are free of the immediate buffering and neutralizing effect of the carbonate rocks on acid water solutions. Surely mobilization processes (e.g. oxidation reactions) were at work in the Galena area. They were likely operable in premining time. These processes contributed free sulfuric acid and soluble metallic sulfates to the circulating ground water. These findings are in agreement with those reported by Broadhead (1874), Hay (1893), and Mudge (1879, 1883) in their early studies of the area.

Finally, in a computer simulation of the premining water quality of ground and surface water in the vicinity of Short creek in Galena, Kansas, the same conclusions are proven using accepted geochemical modelling techniques.

The modelling shows beyond a doubt that natural processes of weathering and erosion can also cause significant contamination and degradation of natural waters in a mineralized region--especially where sulfide ore bodies are subjected to oxidation by surface and/or shallow ground waters. This finding again should provide no surprise, as this is exactly what has been found and reported worldwide whenever sulfide ore bodies are attacked or exposed as they obviously were in premining time in the Galena, Kansas, area.

Clearly, as the modelling shows, concentrations of lead, zinc, Cd, Ni, and other elements, exceeding present-day drinking water and stream water standards were common occurrences in Short Creek and the shallow ground water system in the vicinity of Galena, Kansas in premining time.

REFERENCES

- Bailey, E. H. S., 1902. Special Report on Mineral Waters. Univ. Geol. Survey of Kansas, v. 7, 343 p. State Printer, Topeka.
- Broadhead, G. C., 1874. Report of the Geol. Survey of State of Missouri, 734 pp. Esp. chapters 22-28, pp. 381-502: Report on lead region of southwest Missouri.
- Brockie, D. C., Hare, E. H., Jr., and Dingess, P.R., 1968. The Geology and Ore Deposits of the Tri-State District of Missouri, Kansas, and Oklahoma; pp. 400-430, in Ore Deposits of the United States, 1933/1967, Ed. by J.D. Ridge: Amer. Inst. Mining, Metallurgical, and Petrol. Engineers, NY, 991 pp.
- Cameron, E. M., 1977. Geochemical Dispersion in Lake Waters and Sediments from Massive Sulfide Mineralization, Agricola Lake Area, Northwest Territories. J. Geochemical Exploration, v. 7, p. 327-348.
- Department of Natural Resources, 1976. State of Wisconsin. Environmental Impact Statement for Flambeau Mining Corporation Proposed Copper Mine, Rusk County, Wisconsin, 201 pp.
- _____, 1986. State of Wisconsin. Final Environmental Impact Statement, Exxon Coal and Minerals Co. Zinc Copper Mine, Crandon, Wisconsin, 446 pp.
- Environmental Protection Agency, 1984. Doc. EPA 10-AK-WULIK-NPDES-84 Environmental Impact Statement (Draft), Red Dog Mine Project, Northwest Alaska, pp. IV 24-30.
- Environmental Protection Agency, 1986. Doc. WA No. 127.7LB9.0 Final Draft Phase I - Remedial Investigation Report Cherokee County, Galena Subsite - Contract No. 68-01-6692. Ch₂M Hill. 135 pp. and appendices.
- Feder, G. L., Skelton, John, Jeffery, H. G., and Harvey, E. J., 1969. Water Resources of the Joplin area, MO: Missouri Geological Survey and Water Resources, Water Resources Report 24, 97 pp.
- Felmy, A. R., Girvin, D. C., and Jenne, E. A., 1983. MINTEQ - a Computer Program for Calculating Aqueous Geochemical Equilibria: Final Project Rept., E.P.A. Contract No. 68-03-3089: Athens, GA, 391 pp.
- Garrels, R. M. and Christ, C. L., 1965. Solutions, Minerals, and Equilibria: Freeman, Cooper, and Co., San Francisco, CA, 450 pp.

- Hawkes, H. E. and Webb, J. S., 1962. Geochemistry in Mineral Exploration, pp. 230-246. Harper & Row, New York.
- Haworth, Erasmus, 1904, Lead and Zinc: University Geological Survey of Kansas Special Report, v. 8, 509 pp. (with W. R. Crane and A. F. R. Rogers), State Printer, Topeka.
- Hay, Robert, 1893. Lead and Zinc. Eighth Biennial Report of the State Board of Agriculture Kansas, 1891-1892, v. 13. State Printer, Topeka.
- Henderson, T., 1985. Geochemistry of Ground-Water in Two Sandstone Aquifer Systems in the Northern Great Plains in Parts of Montana and Wyoming; U.S. Geological Survey Prof. Paper 1402-C, 84 pp.
- Intera Environmental Consultants, 1983. PHREEQE: a Geochemical Speciation and Mass Transfer Code Suitable for Nuclear Waste Performance Assessment: U.S. Dept. of Energy Rept. ON-1-435, Intera Environ. Consults., 11999 Katy Freeway, Suite 610, Houston, TX 77079, 304 pp.
- Krauskopf, K., 1967. Introduction to Geochemistry, 721 pp. McGraw-Hill, New York.
- Levinson, A. A., 1974. Introduction to Exploration Geochemistry, pp. 72-86. Applied Publishing Ltd., Calgary.
- Lindsay, W. L., 1979. Chemical Equilibria in Soils: Wiley-Interscience, New York, NY, 449 pp.
- Macfarlane, P. Allen, and Hathaway, Lawrence R., 1987. The Hydrology and Chemical Quality of Ground Waters from the Lower Paleozoic Aquifers in the Tri-State Region of Kansas, Missouri, and Oklahoma. Kansas Geological Survey, Ground Water Series 9, 37 pp.
- Macfarlane, P. A., Whittemore, D., and Hathaway, L. R., 1981. A report to the Kansas Department of Health and Environment on the hydrogeology and chemical quality in the Lower Paleozoic aquifers in southeast Kansas and adjoining areas of Missouri and Oklahoma: Kansas Geological Survey, Open-file Report 81-16, 48 pp.
- May, E. R., 1977. Flambeau - A Precambrian Supergene Enriched Massive Sulfide Deposits. Vol. 1 Geoscience Wisconsin, Geol. and Natural History Survey, Madison, Wisc., p. 1-26.
- Miller, W. R., Ficklin, W. H., and Learned, R. E., 1982. Hydrogeochemical Prospecting for Porphyry Copper Deposits in the Tropical-Marine Climate of Puerto Rico: J. Geochemical Exploration, v. 16, p. 217-233.

- Mudge, B. F., 1879. Short Creek Diggings in First Biennial Report of State Board of Agriculture, Kansas, 1877-1878, v. 6, p. 82-84. State Printer, Topeka.
- Mudge, B. F., 1883. Paleozoic Area in Third Biennial Report of State Board of Agriculture, Kansas, 1881-1882, v. 8, p. 576-578. State Printer, Topeka.
- Nickel, E. H., 1984. The Mineralogy and Geochemistry of the Weathering Profile of the Teutonic Bore Cu-Pb-Zn-Ag Sulfide Deposits: J. Geochemical Exploration, v. 22, p. 239-264.
- Parker, H. N., 1911. Quality of the water supplies of Kansas: U.S. Geological Survey Water-Supply Paper 273, 375 pp.
- Parkhurst, D. L., Thorstenson, D. C., and Plummer, L. N., 1980. PHREEQE - A Computer Program for Geochemical Calculations: U.S. Geol. Survey Water-Resources Invests. 76-13, 61 pp.
- Ritchie, Everett, 1986. Guide Book to the Tri-State Mineral Museum: Missouri Southern Foundation - City of Joplin, A&J Printing, Nixa, Missouri, 83 pp.
- Rose, A. W., Hawkes, H. E., and Webb, J. S., 1979. Geochemistry in Mineral Exploration, 2nd Ed.: Academic Press, NY, 657 pp.
- Sangameshwar, S. R. and Barnes, H. L., 1983. Supergene processes in zinc-lead-silver sulfide ores in carbonates: Econ. Geol., v. 78, p. 1379-1397.
- Schweitzer, P., 1892. Mineral Waters of Missouri: Geol. Survey of Missouri, v. 3, 256 pp. p. 30-37. Geol. Survey, Pub., Jefferson City, Mo.
- Seevers, W. J., 1975. Description of the surficial rocks in Cherokee County, southeastern Kansas, Geology Series No. 1, 7 pp.
- Siebenthal, C. E., 1915, Origin of the zinc and lead deposits of the Joplin region, Missouri, Kansas, and Oklahoma: U.S. Geological Bulletin 606, 283 pp.
- Smith, W. S. T., 1905. Water resources of the Joplin district, Missouri-Kansas, in contributions to the hydrology of the Eastern United States: U.S. Geological Survey Water-Supply Paper 145, pp. 74-83.
- Spruill, T. B., 1984. Assessment of water resources in lead-zinc mined areas in Cherokee County, Kansas and adjacent areas: U.S. Geological Survey Open-File Report 84-439, 102 pp.

- Spruill, T. B., 1987. Assessment of water resources in lead-zinc mined areas in Cherokee County, Kansas, and adjacent areas: U.S. Geological Survey Water-Supply Paper 2268, 68 pp.
- Steele, K. F. and Dilday, T. F., 1985. Hydrogeochemical Exploration for Mississippi Valley-Type Deposits, Arkansas, U.S.A., J. Geochemical Exploration, v. 23, p. 71-79.
- Vandelannoote, R., Blommaert, W., Sadurski, A., Van'T Dock, L., Gijbels, R., Van Grieken, R., Bosch, B., Leleu, M., Rochon, J., Sarcia, C., and Sureau, J. F., 1984. Trace-Elemental Anomalies in Surface Water Near a Small Lead-Zinc Mineralization at Menez-Albot (Brittany, France). J. Geochemical Exploration, v. 20, p. 33-46.
- Winslow, Arthur, 1894. Lead and Zinc Deposits of Missouri: Missouri Geological Survey, v. 6, 763 pp. (esp. pp. 596-600, 544-596).

APPENDIX - VITAE

VITA

Full Name: ANGINO, ERNEST E.

Born: 16 February, 1932, Winsted, Connecticut

Education: Lehigh Univ. B.S. 1954, Major Geophysics
Univ. of Kansas M.S. 1958, Major Geology
Univ. of Kansas Ph.D. 1961, Major Geochemistry

Member: Professional:
Society of Economic Paleontologists and Mineralogists
American Association for the Advancement of Science
Geochemical Society
Society Environmental Geochemistry and Health
Geological Society of America
Kansas Geological Society
American Association of Petroleum Geologists
International Association of Geochemistry & Cosmochemistry

Honorary:
Sigma Xi

Listed in:
American Men of Science
Who's Who in Midwest
Leaders in American Science
Leaders in American Education
International Biography

Honors: Angino Buttress, Antarctic 78 14'S, 158 45'E - 1967
Antarctic Service Medal of DOD for Antarctic Research - 1969
NSF Summer Fellowship Radiochemistry, ORNL - 1963
Mayor, City of Lawrence, Kansas - 1984-85

National Experience:
Secretary, Geochemical Society - 1970-76; Councilor - 1970-76
U.S. National Committee on Geochemistry - 1971-77
U.S. National Committee on Environmental Geochemistry in
Relation to Health & Disease - 1973-76, Co-Chman. -1975-76
Councilor: Society of Environmental Geochemistry & Health -
1972-75
Vice Chairman: Comm. on Research & Development, National Gas
Survey, Federal Power Commission - 1975-77
President: Society for Environmental Geochemistry and Health -
1978-79
Member: Coordinating Council, National Gas Survey, Federal
Power Commission - 1975-77
Member: Research Committee on Water Chemistry, American Geoph.
Union - 1972-76
Member: Publications Comm., Society of Economic
Paleontologists and Mineralogists - 1977-

Member: Argonne National Lab. Review Comm. Energy & Environ. Systems and others. 1978-
Chairman: Review Committee EES, Argonne National Lab. - 1980 and 1981
Treasurer: International Association of Geochemistry and Cosmochemistry - 1980-
Member: NAS Comm. on Disposal of Hazardous Industrial Wastes - 1981-83
Member: Finance and Headquarters Comm. Soc. Econ. Paleo. Min. 1982-

Industrial Experience:

June 1953 - September 1953: Seismic computer trainee; Geophysical Service, Ind.; Dallas, Texas.
June 1954 - September 1954: Seismic computer (Geophysics); Western Geophysical Co.; Brookhaven, Mississippi
January 1955 - January 1957: U.S. Army Signal Corp.; Geophysics section; Fort Monmouth, New Jersey.
May 1957 - September 1957: Geophysicist, Kansas Geological Survey (Gravity and Resistivity).
1962 - Present: Consultant to several concern on water chemistry and pollution (including Dow Chemical Company; Oceanics, Inc.; Bureau Commercial Fisheries; Fisheries Research Board Canada; U.S. Coast & Geodetic Survey; Ocean Mining, Inc.; Envicon, Inc.; Oak Ridge National Laboratories; U.S. Geological Survey Consultant on water chemistry and trace element geochemistry and chemistry and health to Midwest Research Institute. Consultant on water chemistry and trace element geochemistry and health to Kansas Water Resources Board and Kansas Geological Survey; and other national committees concerned with water problems.

[CONSULTING]

Academic and Research Experience:

1961 - Present: Principal Investigator and Director of numerous grants for research from NSF, ONR, EPA, Kansas Water Resources Research Institute (Kansas Water Resources Board), Mobil Foundation, and others.
Have published more than 90 research papers and several books related to thermoluminescence, Antarctica, trace element geochemistry (High Level Radioactive Waste disposal), pollution, and aqueous geochemistry in major journals (see below under publications).
Editor, Mineralogical and Geological Chemistry, Chemical Abstracts Journal. 1967-73.
Associate Editor, Journal of Sedimentary Petrology. 1972-82-
Associate Editor, Modern Geology. 1973-84.
Secretary, Geochemical Society. 1970-76.
Instructor of Geochemistry, Dept. of Geology, University of Kansas, Lawrence, Kansas, 1961-62.
Assistant Professor of Geochemistry, Dept. of Oceanography and Meteorology, Texas A&M University, College Station, Texas. 1962-65.

Chief, Geochemistry Section, State Geological Survey,
University of Kansas, Lawrence, Kansas. 1965-70.
Professor of Civil Engineering, University of Kansas (Water
Chemistry), 1971 - , Assoc. Prof., 1967-71.
Associate Director and Associate State Geologist, State
Geological Survey, University of Kansas, Lawrence, Kansas,
1970-72.
Chairman and Professor, Department of Geology, University of
Kansas, 1972 - .
Member, Editorial Board, Geology, 1975-78.
Member, Editorial Board, Environmental Geology, 1977- .

Bibliography (Books):

- 1965 Thermoluminescence Bibliography, TID-3911 (Rev. 2), U.S.
Atomic Energy Commission, Div. of Technical Information
(with N. Grogler), 97 pp.
- 1967 Atomic Absorption Spectrometry in Geology, Elsevier
Publishing Co. (with G. K. Billings), 154 pp.
- 1967 Proceedings of Third Forum on Geology of Industrial
Minerals (Editor with R. Hardy), 183 pp.
- 1969 Geochemistry of Subsurface Brines, Elsevier Publishing
Co., (with G. K. Billings), 375 pp.
- 1972 Atomic Absorption Spectrometry in Geology, Elsevier
Publishing Co. (with G. K. Billings), 2nd Edition, 200 pp.
- 1979 Geochemistry of Bismuth, Dowden, Hutchinson and Ross,
Inc. (with D. T. Long, Eds.), 400 pp.

Consulting: Within the last 10 years consulting work has been conducted for many concerns with problems related to inorganic pollution, trace element geochemistry and rock properties, and high level radioactive waste burial. Studies related to identification of hydrocarbons in sediments and water and trace element relations have been both published and reported privately. Additional work has been done with means of identifying sources of petroleum pollution as well as means of removal of crudes, bunker C, etc. from water once a spill has occurred. Instrumental experience in these research studies includes gas chromatography, IR, ESR, atomic absorption spectrometry (X-ray diffraction), etc.

Present Research Programs:

I am engaged in several research programs related to aqueous geochemistry, chemistry, such as use of Electron Spin Resonance in water chemistry studies. Investigation and geochemistry of Economic Utilization of Subsurface Brines, and an investigation of effect of suspended load on water chemistry.

Chemical complexing in aqueous solutions. Presently we are actively engaged in studying factors related to burial of high-level radioactive wastes. More recently research studies have directed to geochemistry of leachates from fly ash, coal piles, and sanitary land fills.

We have initiated and now have underway research on the origin, distribution and abundance of nitrogen and hydrogen gases in the natural environment.

Another study involves the origin and mineralogy of Polar Climate efflorescences.

LIST OF PUBLICATIONS

1. Thermoluminescence

- 1959 The Effects of Trace Elements on Natural Thermoluminescence, Compass, V. 36, p. 298-303 (with F. R. Siegel).
- 1959 Pressure Effects on Thermoluminescence of Limestone Relative to Geologic Age, J. Geophysical Research, 64, p. 569-574.
- 1959 Some Effects of Pressure on Thermoluminescence of Limestone, J. Geophysical Research, V. 64, p. 1638-1640.
- 1961 Pressure Thermoluminescence, Proceedings of 1960 International Conference on Color Centers and Crystal Luminescence, Bull. Electrotechnio Instituto Nazionale, Turin, Italy, p. 95-110.
- 1962 Thermoluminescence of Thoria, J. Chem. Physics, V. 36, p. 1105-1106 (with E. H. Greener and W. Hirthe).
- 1962 Thermoluminescence of Alpha Niobia Pentoxide, J. American Ceramics Soc., V. 45, p. 93 (with E. H. Greener and G. Fehr).
- 1964 The Effects of Non-hydrostatic Pressures on Radiation Damage Thermoluminescence, Geochimica et Cosmochimica Acta, V. 28, p. 381-388.
- 1964 Some Effects of Pressure on the Thermoluminescence of Amblygonite, Pectolite, Orthoclase, Scapolite, and Wollastonite, American Mineralogists, V. 49, p. 387-394.
- 1967 Thermoluminescence of Some Carbonates, ThO and BatiO , Proceedings 1st International Conference on Luminescence Dosimetry, Stanford Univ., June 1965, AEC Symposium Series 8, p. 158-165.

2. Antarctic

- 1961 Basal Sedimentary Section at Windy Gully, Taylor Glacier, Victoria Land, Antarctica, Bull. GSA. V. 72, p. 781-86 (with E. J. Zeller and M. D. Turner).

- 1962 Reconnaissance Geology of Lower Taylor Valley, Victoria Land, Antarctica, Bull. GSA, V. 73, p. 1553-62 (with M. D. Turner and E. J. Zeller).
- 1962 Air Temperature from Taylor Glacier Dry Valley, Victoria Land, 1961, Polar Record, V. 11, p. 283-84 (with K. B. Armitage and J. C. Tash).
- 1962 Sedimentologic Study of Two Members of the Beacon Formation Windy Gully, Victoria Land Antarctic, Trans. Kan. Acad. Sci., V. 65, p. 61-69 (with D. E. Owen).
- 1963 Preliminary Geochemical Study of Lakes Bonney and Vanda, Victoria Land, Antarctica, J. Geology, V. 71, p. 89-96 (with K. B. Armitage).
- 1963 New Isotopic Age Measurements from McMurdo Sound Area, Antarctic, Nature, V. 199, No. 4894, p. 805, (with W. C. Pearn and D. Stewart).
- 1964 Antarctic Orogenic Belts as Delineated by Absolute Age Dates SCAR, Symposium on Antarctic Geology - Capetown 1963, p. 551-556 (with M. D. Turner).
- 1964 A physicochemical and Limnological Investigation of Lake Bonney, Victoria Land, Antarctica, Limnology and Oceanography, V. 9, p. 207-217 (with J. C. Tash and K. B. Armitage).
- 1965 A Chemical and Limnological Study of Lake Vanda, Victoria Land, Antarctica, Kansas Science Bulletin, June 1965 issue, V. 45, No. 10, p. 1097-1118 (with K. B. Armitage and J. C. Tash).
- 1966 "Ross Sea (sediments, geol. structure and oceanography)" Rheinhold Encyclopedia of Earth Science, V. 1, Oceanography, p. 751-753 (with L. K. Lepley).
- 1966 Petrology of Bottom Sands from Lakes Bonney and Vanda, Victoria Land, Antarctica. Trans. Kans. Acad. Sci., V. 69, p. 233-237 (with J. F. Hubert).
- 1966 Uranium and Thorium in Antarctic Glacial Marine Sediments. Ocean. Mag., V. 18, p. 57-62 (with Y. Sugimura).

3. Trace Element-Geochemistry

- 1958 The Operations of Seismic Field Party, Compass, V. 35, p. 92-97.
- 1959 Colloidal Deposition of Minerals - A Brief Survey, Compass, V. 36, p. 152-156.
- 1964 Far Infrared Spectra of Montmorillonite, Kaolinite, and Illite, Nature, V. 204, p. 569-572.

- 1965 Ionic Content of Antarctic Ice Samples, Polar Record, V. 12, p. 407-409 (with K. B. Armitage and J. C. Tash).
- 1965 Fixing of Fallout Nuclides by Free Floating Marine Organisms, S. Fluitans and S. Natans, Institute Marine Science, V. 11, p. 1973-1978 (with J. Simek and J. Davis).
- 1965 The Determination of Strontium in Oil Field Brines by Atomic Absorption Spectrometry. Bull. Can. Petrol. Geol., V. 13, p. 529-531 (with G. K. Billings).
- 1966 Li Content of Sea Water by Atomic Absorption, Geochim. et Cosmochim. Acta, V. 30, p. 153-158 (with G. K. Billings).
- 1966 Geochemistry of Antarctic Pelagic Sediments, Geochim et Cosmochim. Acta., V. 30, pp. 939-962.
- 1966 Observed Variations in the Strontium Concentration of Sea Water, Chem. Geol., V. 1, pp. 145-153 (with G. K. Billings and N. Andersen).
- 1966 Trace Elements in Antarctic Bottom Sediments (Pacific Sector) Theinhold Encyclopedia of Earth Science, V. 1, Oceanography, pp. 38-40.
- 1966 Application of Pattern Analysis to the Classification of Oil Field Brines. Colloquium on Classification Procedures - Comp. Contrib. 7, Kansas Geol. Survey, pp. 53-56 (with C. O. Morgan).
- 1967 Far Infrared (400-30cm) spectra of some Carbonate Minerals. Amer. Mineralogist, V. 52, pp. 137-148.
- 1967 The Determination of Calcium and Magnesium in Carbonate and Silicate Rocks by Atomic Absorption. Kansas Geol. Survey, Bull. 187, Part 1, pp. 9-11 (with O. K. Galle).
- 1967 Distribution of Iron in the Various Components of Recent Carbonate Sediments. Kansas Geol. Survey, Bull. 187, Part 1, pp. 3-5.
- 1967 Water Quality in the Kansas River, Now and in the Future, with W. O'Brien, T. C. Waugh, and E. A. Stoltenberg, Bull. Eng. & Arch., No. 57, pp. 37-48.
- 1967 Oil Field Brines - A Wasted Resource, Proceedings of Third Forum on Geology of Industrial Minerals Spec. Dist. Pub. 34, KGS, pp. 120-124.
- 1968 Effects of Suspended Material on Water Wuality. IUGG-IASH Symposium Proceed., pp. 120-128 (with W. J. O'Brien).

- 1968 Sorption of radionuclides on *Sargassum fluitans* and *S. natans*, Second Nat'l. Conference on Radioecology (with J. Simek and J. A. Davis). Symposium on Radioecology. AEC TID 4500, pp. 505-508.
- 1968 Trace Element Chemistry, Heavy Minerals and Sediment Parameters of Weddell Sea Sediments, *J. Sed. Pet.*, V. 38, pp. 634-642 (with R. Andrews).
- 1968 Sulphate and Carbonate Efflorescences from the Antarctic Interior. *Antarctic J. of U.S.*, V. 3, No. 6, pp. 239-241 (with P. Tasch).
- 1969 Chemical Composition of Selected Kansas Brines as an Aid to Interpreting Change in Water Chemistry with Dept., *Chem. Geol.*, V. 4, pp. 325-337 (with R. Dingman). Special issue on: "Geochemistry of Subsurface Brines" (Eds. E. E. Angino and G. K. Billings).
- 1969 Far Infrared Absorption Spectra of Plagioclase Feldspars, *Kansas Geol. Survey, Bull.* 194, Part 1, pp. 9-12.
- 1969 Elemental Analysis in Geochemistry, Part A. Major Elements. (Methods in Geochemistry and Geophysics, 8, A. Volborth), Elsevier (a review), *Sedimentology*, V. 13, pp. 320-321.
- 1969 Fe, Mn, Ni, Co, Sr, Li, Zn, and SiO₂ in Streams of the Lower Kansas River Basin. *Water Resources Research*. V. 5, pp. 698-705 (with O. K. Galle and T. C. Waugh).
- 1969 Pollution Problems and Solutions in Kansas. *Kansas Water News*, No. 3, pp. 105 (with W. J. O'Brien). Also same title, more detail in *Trans. Nineteenth Annual Conference on Sanitary Engineering*. Univ. Kansas Publications, *Bull. of Engineering and Arch.*, No. 60, pp. 19-25.
- 1969 Iron Rich Layers in Sediments from the Gulf of Mexico. *J. Sed. Petrography*, V. 39, pp. 1412-1419 (with J. Watson).
- 1970 Thermoluminescence of Geological Materials. Ed. by D. J. McDougall, Academic Press (a book review). *Goederma*, pp. 181-182.
- 1970 Arsenic in Detergents: Possible Danger and Pollution Hazard. *Science*, V. 168, pp. 389-390 (with L. M. Magnuson, T. C. Waugh, O. K. Galle, and J. Bredfeldt).
- 1970 Arsenic and Water Pollution Hazard. *Science*, V. 170, pp. 871-872 (with L. M. Magnuson, et. al.).
- 1970 Selective Element Recovery from Oil Field Brines. *Water Resources Research*. V. 6, pp. 1501-1504.

- 1971 Lead Isotopes and Metallic Sulphides as Exploration Guides in Mid-Continent Paleozoic Rocks. Can. Inst. Mining. Spec. Vol. 11, Geochemical Exploration, pp. 453-456 (with E. D. Goebel).
- 1971 Precipitation of Deep-Sea Palygorskite and Sepiolite. Earth and Planetary Sci. Letters, V. 11, pp. 324-332 (with F. Bowles, J. Hosterman, and O. K. Galle).
- 1971 The Disposal of High-Level Radioactive Waste in Salt - Why Kansas? Kansas Mineral Industry Report 1970, Sp. Dist. Pub. 55, pp. 33-36.
- 1971 Identification of Manganese in Water Solutions by Electron Spin Resonance, Advances in Chemistry Series, V. 106, Nonequilibrium Systems in Natural Water Chemistry, pp. 229-308 (with L. Hathaway and T. Worman).
- 1972 Effects of Urbanization on Storm Water Runoff Quality: A Limited Experiment, Naismith Ditch, Lawrence, Kansas, Water Resources Res., V. 8, pp. 135-140 (with L. Magnuson and G. Stewart).
- 1972 Bismuth: The Element and Its Geochemistry. Encyclopedia of Geochemistry and Environmental Sciences. R. Fairbridge (ed.), Van Nostram D. Reinhold, New York, pp. 82-84.
- 1972 Trace Element Geochemistry of Carbonate Sediments - Yucatan Shelf, Mexico. Contrib. to Geol. & Geophys. Ocean. Gulf of Mexico, Gulf Publ. Co., Houston, Texas, pp. 281-290 (with J. Harding and W. Bryant).
- 1973 Population Dynamics of Pond Zooplankton. I. Diaptomus pallidus Herrick. Hydrobiologia, V. 42, pp. 295-333 (with K. B. Armitage, Sr. Author, and B. Saxana).
- 1973 Population Dynamics of Pond Zooplankton. II. Daipatomus ambigu Scourfield. Hydrobiologia, V. 42, pp. 491-507 (with K. B. Armitage, Sr. Author, and B. Saxana).
- 1973 Putting Radioactive Waste on Ice - A proposal for an International Radionuclide Depository in Antarctica. Science and Public Affairs: Bull. Atomic Scientists, V. 24, Jan. 1973, p. 4, et. seq. (with E. J. Zeller and D. F. Saunders)
- 1973 Application of Electron Spin Resonance to the Study of Crude Petroleum, Modern Geology, V. 4, pp. 225-231 (with P. Virmani and E. J. Zeller).

- 1974 Mineralogy of Suspended Sediment and Concentration of Fe, Mn, Zn, Ni, Cu, and Pb in Water and Fe, Mn, Pb, Ni in Suspended Load of Selected Kansas Streams. Water Resources Research (with L. M. Magnuson and T. C. Waugh), V. 10, pp. 1187-1191.
- 1974 A proposal of Establishment of a Permanent International High-Level Radioactive Waste Depository in Antarctica; in OECD-IAEA Symposium, Paris (1973) on: Management of Radioactive Wastes from Fuel Reprocessing, pp. 431-446 (with E. J. Zeller and D. F. Saunders).
- 1974 Portions of chapters on: Chromium, Lithium, Analytical Methods, and Sampling, Sample Preparation, and Storage for Analysis in "Geochemistry and the Environment, V. 1, The Relation of Selected Trace Elements to Health and Disease," 113 p. National Acad. Sci., National Res. Council.
- 1976 Antarctica: A Potential Disposal Site for the World's High-Level Radioactive Wastes (with D. F. Saunders and E. J. Zeller). Modern Geology, V. 6, pp. 31-36.
- 1976 Occurrence of Copper Sulfides in the (Permian Age) Milan Dolomite, South Central Kansas (with D. T. Long) Economic Geology, V. 71, pp. 656-661.
- 1976 Antarctica - A Potential International Burial Area for High-Level Radioactive Wastes, "An Additional Appraisal." Bull. Int. Assoc. Eng. Geologists, V. 14, (with G. Dreschhoff and E. J. Zeller), pp. 173-178.
- 1976 Potential Uranium Host Rocks and Structures in Central Great Plains. Kansas Geol. Series 2, 55 p. (with E. J. Zeller, senior author and others).
- 1977 The Role of Trace Metals in Calcium Urolithiasis, Investigative Urology, V. 14, (with J. L. Meyer), pp. 347-350..
- 1977 The Chemical Quality of Drinking Water and Chronic Disease. Environ. Sci. and Tech., V. 11, pp. 660-665 (with B. Wixson and I. Smith).
- 1977 Chemical Speciation of Zn, Cu, Cd, and Pb in Fresh Water, Estuarine, and Marine Environments (with D. T. Long). Geochem. Cosmochem. Acta, V. 41, pp. 1183-1194.
- 1977 High-Level and Long-Lives Radioactive Waste Disposal. Science, V. 198, No. 4320, pp. 885-890.

- 1978 The Disposal of Radioactive Wastes in the Antarctic Ice Sheet: an Environmental Impact Assessment. Symp. volume on: Environmental Impace in Antarctica, B. Parker, Ed., VPI Press (with E. J. Zeller), pp. 279-294.
- 1978 Determination of Sub-nanogram amounts of Ag in Rainwater by Stable Isotope Dilution (with M. E. Bickford and others), Anal. Chem., V. 50, pp. 469-471.
- 1978 Water: Trace Elements in Solution: in Geochemistry and the Environment, V. III, Distribution of Trace Elements Related to Occurrence of Certain Cancers, Cardiovascular Diseases, and Urolithiasis (with several authors), NAS-NRC, 1978, pp. 32-48
- 1979 Geochemistry of Bismuth. Benchmark Series, Dowden, Hutchinson, and Ross, Inc. (with D. T. Long), 425 p. (Book).
- 1979 Nitrate and Phosphate: Time-Trend Concentrations in Selected Kansas Streams (with P. Hulen). Trans. Kansas Academy of Sciences, V. 82, pp. 73-83.
- 1979 Geochemistry of Drinking Water as Affected by Distribution and Treatment: in Geochemistry of Water in Relation to Cardiovascular Disease, NAS-NRC, pp. 3-13.
- 1980 Trace Element, Mineral and Size Analysis of Suspended Flood Materials from Selected Eastern Kansas Rivers (with H. Schneider). Journal of Sedimentary Petrology, V. 50, pp. 1271-1278.
- 1981 Effect of Leachate Solutions from Fly and Bottom Ash on Ground Water Quality (with D. A. Kopsick). Journal of Hydrology, v. 54, pp. 341-356.
- 1982 The Mobilization of Selected Trace Metals from Shales by Aqueous Solutions: Effects of Temperature and Ionic Strength (with D. T. Long). Econ. Geol., V. 77, pp. 646-652.
- 1983 Potential Oil Recovery from Kansas Oil Shales, Kansas Geological Survey - Energy Resource Series 22, 39 p. (with D. G. Schlinsog).
- 1983 Chapter titled: Geochemistry and Water Quality - pp. 171-198 published in Applied Environmental Geochemistry, Ian Thornton (Ed.), Academic Press
- 1984 Geology, Composition, Isotopes of Naturallly Occurring H₂/N₂ Rich Gas from Wells near Junction City, Kansas. Oil and Gas Journal, May 7, 1984 pp. 215-222. (with E. D. Goeble, R. M. Coveney, E. J. Zeller and G. M. Dreschhoff).

- 1984 Strategic Minerals - America's Achilles Heel? Modern Geology, with R. W. McColl, V. 8, pp. 307-310.
- 1984 Hydrogen and Nitrogen - Origin, Distribution, and Abundance -- A Follow Up: Oil and Gas Journal, Dec. 3, 1984, pp. 142-146 (with 4 other authors, Angino Senior Author).
- 1984 Geochemical Prospecting for Thorium and Uranium Deposits, J. Geochem. Expl., V. 20, 1984, pp. 99-100 (Book Review).
- 1984 International Minerals - A National Perspective. Amer. Assoc. Petrol. Geol. Bull., V. 68, 1984, pp. 789-90 (Book Review).
- 1985 Nuclear Waste Management - A Review of Issues In: Rubey, V. III: Energy: For Ourselves and Our Posterity.
- 1985 Unconventional Recovery of Heavy Oil and Tar Sands. Invited paper: in Exploration for Heavy Crude Oil and Bituman, 1985.
- 1987 Serpentinization and the Origin of Hydrogen Gas in Kansas. Bull. Amer. Assoc. Petrol. Geol., v. 71, pp. 39-48 (with R. M. Coveney, Jr., E. D. Zeller, and G. A. M. Dreschhoff).
- 1987 Unconventional Recovery of Heavy Oil and Tar Sands. Invited paper: in Exploration for Heavy Crude Oil and Bitumen. AAPG Studies #25, pp. 603-605.

Horace G. Jeffery
27 Hawthorne
Rolla, Missouri 65401

EDUCATION-

Arkansas College, Batesville, Arkansas
BS- Chemistry-1952
Many USGS Technical Seminars and Workshops

PROFESSIONAL EXPERIENCE

1952-56--Worked as an Analytical Chemist in a USGS Laboratory in Fayetteville, Arkansas, analyzing water samples by various volumetric, gravimetric, and instrumental methods.

1957-62--Supervised laboratory operations, and worked on several Water Resources investigations. Prepared sections on water quality for inclusion in the project reports.

1962-65--Transferred to Little Rock, Arkansas, worked as the Water Quality specialist on a multi-state investigation of the Ground-water Resources of the Mississippi Embayment, and wrote the water quality sections of reports describing the unconsolidated aquifers that make up the embayment.

1965-72--Transferred to Rolla, MO to develop and manage water quality programs for the Missouri District of the USGS. In addition, I also provided water quality input and expertise to the ongoing water resources studies in the state.

1972-86--Assumed the duties of Assistant District Chief of the Missouri District and shared, with the District Chief, the overall responsibility for the development and implementation of water resources programs in the state and was responsible for day-to-day operation of the District.

May 2, 1986--Retired from Federal Service.

BIBLIOGRAPHY

Attached.

BIBLIOGRAPHY

Horace G. Jeffery

- Miller, D.E., Emmett, L. F., Skelton, John, Jeffery, H. G., and Barks, J. H., 1974, "Water resources of the St. Louis area, Missouri: Missouri Geological Survey and Water Resources, Water Resources Report 30, 114 p.
- Gann, E. E., Harvey, E. J., and Jeffery, H. G., 1971, Water resources of northeastern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA-372.
- Emmett, L. F., and Jeffery, H. G., 1970, Reconnaissance of the ground-water resources of the Missouri River alluvium between Miami and Kansas City, Missouri: U.S. Geol. Survey Hydrologic Atlas 344.
- Emmett, L. F., and Jeffery, H. G., 1969, Reconnaissance of the ground-water resources of the Missouri River alluvium between Kansas City, Missouri and Iowa: U.S. Geol. Survey Hydrologic Atlas 336.
- Emmett, L. F., and Jeffery, H. G., 1969, Reconnaissance of the ground-water resources of the Missouri River alluvium between Jefferson City and Miami, Missouri: U.S. Geol. Survey Hydrologic Atlas 340.
- Emmett, L. F., and Jeffery, H. G., 1968, Reconnaissance of the ground-water resources of the Missouri River alluvium between St. Charles and Jefferson City, Missouri: U.S. Geol. Survey Hydrologic Atlas 315.
- Feder, G. L., Skelton, J., Jeffery, H. G., and Harvey, E. J., 1968, Water resources of the Joplin area, Missouri: Missouri Geol. Survey and Water Resources, Water Resources Report No. 24, 97 p.
- Boswell, E. H., Cushing, E. M., and Hosman, R. L., 1968, Quaternary Aquifers in the Mississippi Embayment with a discussion of quality of the water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448-E.
- Hosman, R. L., Long, A. T., Lambert, T. W., and others, 1968, Tertiary aquifers in the Mississippi Embayment, with discussions of the quality of the water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448-D.
- Speer, Paul R., Hines, Marion S., Janson, M. E., and others, 1966, Low-flow characteristics of streams in the Mississippi Embayment in northern Arkansas and in Missouri, with a section on quality of water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448F.
- May, J. R., Yanchosek, J. J., and Jeffery, H. G., Chemical analyses of the water from selected wells in the Arkansas River Valley from the mouth to Fort Smith, Arkansas: U.S. Geol. Survey open-file report, 1964.

- Speer, Paul R., Hines, Marion S., Calandro, A. J., and others, 1966, Low-flow characteristics of streams in the Mississippi Embayment in southern Arkansas, northern Louisiana, and northeast Texas, with section on quality of the water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448G.
- Speer, Paul R., Perry, W. J., McCabe, John A., Lara, O. G., and others, 1965, Low-flow characteristics of streams in the Mississippi Embayment in Tennessee, Kentucky, and Illinois, with a section on quality of the water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448H.
- Boswell, E. H., Moore, G. K., MacCary, L. M., and others, 1965, Cretaceous aquifers in the Mississippi Embayment, with discussion of quality of the water by H. G. Jeffery: U.S. Geol. Survey Prof. Paper 448C.
- Murphy, J. J., and Jeffery, H. G., 1963, Supplement B-9, Progress report on the quality of water monitoring program, 1959-1961: (A supplement to the report on ground water geology and hydrology of the lower Arkansas and Verdigris River Valleys) U.S. Geol. Survey Administrative report.
- Harvey, E. J., Golden, H. G., and Jeffery, H. G., 1965, Water resources of the Pascagoula area, Mississippi: U.S. Geol. Survey Water-Supply Paper 1763.
- Bedinger, M. S. and Jeffery, H. G., 1964, Ground water hydrology of the lower Arkansas River Valley: U.S. Geol. Survey Water-Supply Paper 1669V.
- Bedinger, M. S., Emmett, L. F., and Jeffery, H. G., 1963, Ground-water potential of the alluvium of the Arkansas River between Little Rock and Fort Smith, Arkansas: U.S. Geol. Survey Water-Supply Paper 1669L.
- Bedinger, M. S., and Tanaka, H. H., 1960, Report on the ground water hydrology of the lower Arkansas and Verdigris River Valleys: U.S. Geol. Survey Administrative Report, p. 138-166, pls. 68-73.
- Geurin, J. W. and Jeffery, H. G., 1957, Chemical quality of surface waters of Arkansas, 1945-55, A Summary: Univ. of Ark. Eng. Expt. Sta. Bull. 25.

RESUME

Robert B. Leonard, Hydrogeologist, Rt. 6, Box 68, Lawrence, Ks. 66046
Tel. (913)-749-3065

Birthdate: Feb. 26, 1926 Robert G./Charlotte M. Hussong-Leonard

Military:

1943-46 Basic Engineering (ASTRP) Ohio University, Athens, Ohio
Field Artillery Instrument and Survey, Fort Bragg, N.C.;
Combat Engineers basic training, Fort Leonard Wood, Mo.
Field Artillery, Philippine Campaign; Honorable discharge.

Education:

1943 Graduation (Valedictorian) Hargrave Military Acad. Chatham, Va.
1950 BS. (Geology) Massachusetts Institute of Technology, Cambridge,
Mass. Elective coursework directed mainly toward mining geology
and geochemistry.
Thesis: "The geology of the McAras Brook area, Nova Scotia".
Dept. Mines Ann. Rpt. pt. 2, 1951.
1951 MS. (Geology) Massachusetts Institute of Technology, Cambridge,
Mass. Elective coursework and thesis directed mainly
toward coal and petroleum geology.
Thesis: "Structure and sedimentation in the Port Hood area Nova
Scotia". A geological investigation of two coal basins with
petroleum prospects.
1963 PhD. Virginia Polytechnic Institute, Blacksburg, Va. Coursework
mainly in civil engineering (soil mechanics and foundations) and
earth science (groundwater, geophysics, geochemistry,
sedimentation, clay mineral studies) departments was focused
mainly on soil-water-rock relations.
Dissertation: "Ground-Water Geology along the northwest foot of
the Blue Ridge between Arnold Valley and Elkton, Va.", an
evaluation of the quantity and quality of available ground
water, largely supported by a grant from a major railroad.

Continuing education and training:

Date	Hours	Source	Title.
1963	32	WRD	Systems analysis
	50	Washb rn	Business data processing
1964	40	WRD	Report writing and review for authors.
1965	40	WRD	Accelerated Fortran IV.
1966	16	WRD	Fluorometric techniques seminar.
1968	40	Ks.U.	Statistical Sampling.
	32	WRD	Electrical analog models in hydrology
1969	24	WRD	Water quality, biologic techniques.
1970	40	WRD	Supervisory training.
	80	Ks.U.	Soil mechanics
1971	80	WRD	Adv.Sem. in environmental quality.
	80	WRD	Env. Water Quality, Hydrochem. seminar.
1978	40	WRD	Surface geophysics in hydrologic invest.
	16	Shipley	Workshop in report writing and editing.
1980	40	WRD	Ground-water modeling workshop.

1981	80	WRD	Workshop in geochemical modeling.
	40	WRD	Geochemistry for ground water systems.
1982	16	Prime	Use of Prime minicomputer
1985	40	WRD	Statistical analysis for water quality.

Professional Societies:

Am.Assoc. Advancement of Science.

Am.Assoc. Petroleum Geologists.

Am. Institute of Hydrology (Certified Professional Hydrogeologist).

Society of Sigma Xi.

Assoc. of Ground Water Scientists and Engineers, (National Water Well Association)

Experience:

1948-51. Graduate assistantships, Asst. Instructor in surveying, Nova Scotia Research foundation and M.I.T. field camps.

1951-59. Creole Petroleum Corp., Caracas, Venezuela.

1951-53. Geological and geophysical trainee; exploration geologist, After fairly extensive on-site training in surface and subsurface exploratory methods, my duties consisted mainly of structural and stratigraphic mapping and core drilling followed by proprietary evaluation reports based on analysis of the available geologic and geophysical data.

1954-57. Party Chief, conducting studies in remote areas of Venezuela and Columbia.

1957-59. Regional geologist, senior grade, attached to a divisional exploration group. Concession evaluation, based on surface, subsurface, geophysical, and production data, was the principal duty. Returned to U.S. in 1959 to train for a career in engineering or ground-water geology.

1959-62. Virginia Polytechnic Inst. Blacksburg, Va.; PhD candidate; Research and Teaching assistantships, Part-time instructor, and assistant to ground-water consultant.

1962-87 U.S.Geological Survey, Quality of Water Branch(later Water Resources Division (WRD)). Most assignments were as Project Leader of multidisciplinary projects involving water chemistry, mainly in cooperation with other governmental agencies concerned with hydrology. My principle duties as project leader generally were to:

1. Define the objectives of each project and plan systematic investigations to achieve those objectives.
2. Compile existing pertinent data and information, and, by applying new principles, techniques, and research products, evaluate that data and the need for and the nature of additional basic data collection.
3. Collect representative geologic, geochemical, geophysical, biologic, and hydrologic data using the most appropriate field and laboratory techniques.
4. Coordinate efforts of personnel assigned to the project or related projects and supervise lower-grade project personnel.
5. Maintain liason with cooperators and other agencies, colleges and universities, landowners, industry, consultants, and appropriate research specialists in the area of interest. Exchange information

and coordinate efforts where feasible.

6. Act as consultant and advisor to WRD Staff and to concerned governmental agencies. Represent the WRD, as assigned, in connection with interagency and interdepartmental relations, and its relations with scientific research societies and private interests, including litigation.

7. Author, and collaborate in or advise on the preparation of, scientific reports and papers describing the results of investigations for publication or administrative use. Critically review reports prepared by other professional personnel.

8. Perform other duties as assigned e.g. flood measurements, pumping tests, court appearances, response to requests for information and participation in unrelated investigations.

Principal assignments are described below. Resultant scientific publications are cited in the attached bibliography.

1962-66. Quality of Water Branch, Project office, Topeka, Ks.

1962-67. Project leader of Walnut River Basin project designed evaluate the effects, in time and space, of natural, industrial (mainly oil-field brine pollution), and agricultural factors on chemical quality and use of ground and surface water in the Walnut River Basin.

1965-67. Associate Lecturer (Earth Sciences), Evening college, Washburn Univ. of Topeka.

1966-73. Kansas District office, WRD, Lawrence, Ks.

1966-72. Project leader of Cedar Bluff Irrigation District study designed to evaluate the progressive effects of irrigation on the quantity and chemical quality of ground water and surface water in and adjacent to the newly established irrigation district. Participated in peripheral research defining the movement of trace elements and pesticides in water and soil.

1966-70. Participated in fluorometric time-of-travel surveys of Missouri and Big Blue Rivers as Party Chief of the Kansas Interagency Group. Co-authored a report describing channel degradation in the lower Kansas River valley. Senior author of separate reports evaluating state-wide seepage surveys, seepage-salinity surveys of individual streams in Kansas, quality of inflow to the proposed Towanda reservoir, and application of computer techniques to salinity surveys of low streamflow. Reclassified as Research Hydrologist.

1971-73. Conducted an investigation of the intrusion of saline water from the bedrock and manmade sources into the "Equus Beds" aquifer in the Little Arkansas River basin, Ks., and participated in other studies relating ground-water conditions to land subsidence near oil and gas wells that penetrate salt beds in Kansas.

1973-75 New Mexico Highlands University, Las Vegas, New Mexico.

U.S.G.S. Visiting Professor in Earth Sciences (U.S.G.S. program for Minority Participation in Earth Sciences)

Taught a full load of existing earth-science and environmental courses as well as new courses in ground-water geology, surveying, and air-photo interpretation on the Las Vegas campus, and evening courses in Taos. Designed and received approval for a revised Earth Science curriculum at the university leading to associate (geotechnician),

B.A., or B.S. degrees in Earth Sciences that would fulfill Civil Service requirements for employment.

1975-80. Office of the Regional Hydrologist, WRD, Helena, Montana.
Montana District, WRD, Helena, Montana.

Project Leader - Geothermal Hydrology of southwestern Montana. Investigation consisted of collection, mainly in the field, and compilation of surface and subsurface geologic, geochemical, geophysical and hydrologic information to create a substantive data base used for statewide and national assessments of geothermal resources. Conceptual models of typical hydrothermal systems associated with hot springs or other hydrothermal anomalies were developed, and the suitability of water for use and its potential for pollution of streamflow was estimated. The nature and causes of excessive radioactivity at several locations were studied.

As technical coordinator of related or component studies by Montana universities, state and federal agencies, contractors, and consultants, I performed or actively participated in all phases of the project including surface-water and remote-sensing studies, siting, construction, temperature and geophysical logging, sampling, and testing of wells and test holes, and reporting of results.

Concurrent activities included an investigation of the effect of domestic waste disposal on chemical and biological water quality in shallow alluvial aquifers near Lincoln, Montana, and a preliminary evaluation, based largely on pumping tests, soil maps, and chemical analyses, of shallow "sole source" aquifers in the Helena valley, Montana.

1980-86. Office of the Regional Hydrologist, Central Midwest Regional Aquifer System Analysis (CM-RASA), Lawrence, Ks.

Member (Geochemist) of the central team charged with responsibility for defining and evaluating regional aquifers as to availability and quality of water in an area including all or parts of ten states. Principle duties were generally similar to, but more restricted than those for project leader described above, with the objective of relating the chemical characteristics of the water and plausible geochemical processes to the extent, structure, and mineralogy of regional aquifer-systems, conceptualized flow systems, and use.

Specific tasks, generally performed with other members of the project staff, were to:

- a. Assist in subdivision of the sedimentary section into aquifer and confining systems based mainly on stratigraphic and geochemical information.
- b. Compile, evaluate, and use a machine-readable data base of more than 30,000 available chemical analyses with identifying and supporting data to prepare descriptive maps, sections and diagrams.
- c. Provide, from compiled chemical analyses and electric log interpretations, density values needed for flow modeling.
- d. Prepare reports and review reports of others describing the chemical composition of water in regional aquifer systems.
- e. Specify problem-areas warranting additional studies. Propose, plan, and participate in coordination of those studies.

Since retirement (January 1987), I have been providing voluntary assistance toward completion of the ongoing project.

Additions to Bibliography. Robert B. Leonard, August 1987,

Jorgensen, D.G., Helgesen, J.O., Leonard, R.B., and Signor, D.C., 1986, Equivalent freshwater head and dissolved solids-concentration of water in rocks of Cambrian, Ordovician, and Mississippian age in the northern midcontinent, U.S.A.: U.S. Geol. Survey Miscellaneous Field Studies Map 1835-B, 2 sheets.

Leonard, R.B. and Wood, W.A., 1986, Evaluation of a hydrothermal anomaly near Ennis, Montana: U.S. Geol. Surv. Professional Paper 1044, 127p.

Jorgensen, D.G., Leonard, R.B., Signor, D.C., and Helgesen, J.O., 1986, Central Midwest regional aquifer-system study: in Regional aquifer-system analysis program of the U.S. Geological Survey, Summary of projects, 1978-1984, Ren Jen Sun, ed., U.S. Geol. Survey Circular 1002, p. 132-140.

In preparation.

Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 198__, Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geol. Survey Professional Paper 1414-E,

Baker, C.-., and Leonard, R.B., 198__, Hydrogeochemistry of regional aquifer systems underlying Kansas, Nebraska, and parts of Oklahoma, Missouri, Colorado, Arkansas, Texas, Wyoming, South Dakota, and New Mexico: U.S. Geol. Survey Professional Paper 1414-D,

Robert B. Leonard
Hydrologist

BIBLIOGRAPHY

- Leonard, R. B., Signor, D. C., Jorgensen, D. G., and Helgesen, J. O., 1983, "Geohydrology and hydrochemistry of the Dakota Aquifer, central United States" Water Resources Bulletin, American Water Resources Assoc; vol. 19, no. 6, pp. 903-911.
- Leonard, R. B., Signor, D. C., Jorgensen, D. G., and Helgesen, J. O., 1982, The other High Plains aquifer -- the Dakota sandstone and equivalent units, Abstr., oral presentation. ASCE Natl. Specialty Conference, Lincoln, Neb., May 19-21, 1982.
- Helgesen, J. O., Jorgensen, D. G., Leonard, R. B., and Signor, D. C., 1982, Regional study of the Dakota Aquifer (Darton's Dakota Revisited) Ground Water, July-August 1982, Vol. 20, No. 4, pp. 410-414.
- Leonard, Robert B., and Wood, Wayne A., 1980, Supplemental data from the Ennis and other thermal spring areas, southwestern Montana, 1978-80: U.S. Geological Survey Open-File Report 80-1182, 83 p.
- Leonard, Robert B., Wood, Wayne A., and Boettcher, Arnold J., 1980, Changes in quality of ground water in the Lincoln Area, Montana, 1974-79: U.S. Geological Survey Open File Report 80-1108, 20 p.
- Moreland, J. A., and Leonard, R. B., 1980, Evaluation of shallow aquifers in the Helena Valley, Lewis and Clark County, Montana: U.S. Geological Survey Water Resources Investigations 80-1102, 28 p.
- Leonard, Robert B., and Wood, Wayne A., 1980, Geothermal gradients in the Missoula and Bitterroot Valleys, west central Montana: U.S. Geological Survey Water Resources Investigations 80-89, 19 p.
- Moreland, J. A., Leonard, R. B., Reed, T. E., Clausen, R. O., Wood, W. A., 1979, Hydrologic data from selected wells in the Helena Valley, Lewis and Clark County, Montana: U.S. Geological Survey Open-File Report 79-1676, 57 p.
- Chadwick, R. A., and Leonard, R. B., 1979, Structural controls of hot spring systems in southwestern Montana: U.S. Geological Survey Open-File Report 79-1333, 25 p.
- Leonard, R. B., Brosten, T. M., and Midtlying, N. A., 1978, Selected data from thermal spring areas, southwestern Montana: U.S. Geological Survey Open-File Report 78-438, 71 p.
- Leonard, R. B., Shields, R. R., and Midtlyng, N. A., 1978, Water quality investigation near the Chico and Hunters geothermal lease-application areas, Park and Sweet Grass Counties, Montana: U.S. Geological Survey Open-File Report 78-199, 23 p.

Bibliography - Robert B. Leonard

- (Leonard, R. B., and Janzer, V. J., 1978, Natural radioactivity in geothermal waters Alhambra hot springs and nearby areas, Jefferson County, Montana: Journal of Research, U.S. Geological Survey, Vol. 6, No. 4, July-August, 1978, p. 52-540.
- Leonard, R. B., and Janzer, V. J., 1977, Natural radioactivity in geothermal water Alhambra hot springs and nearby areas, Jefferson County, Montana: U.S. Geological Survey Open-File Report 77-624, 20 p.
- Chadwick, R. A., and Leonard, R. B., 1977, Geothermal investigations in southwestern Montana; A status report: Annual Field Conference, Tobacco Root Soc., 2 p.
- Leonard, R. B., and Kleinschmidt, M. K., 1976, Saline water in the little Arkansas Basin area, southcentral Kansas: Chemical Quality Series No. 3, Kansas Geol. Survey, September 1976, 24 p.
- Leonard, R. B., 1975, Saline water in the Little Arkansas River Basin Area South Central Kansas: U.S. Geological Survey Open-File Report 76-257, April 1976.
- Leonard, R. B., 1974, Changes in the chemical quality of water, Cedar Bluff Irrigation District, Kansas: Kansas Geological Survey Water Quality Series, vol. no. 1, 72 p.
- (Leonard, R. B., and Stoltenberg, G. A., 1972, Compilation of data for water-quality investigation, Cedar Bluff Irrigation District, Kansas, Kansas State Department of Health Bulletin 1-12, 158 p.
- Leonard, R. B., 1972, Chemical quality of water in the Walnut River basin, Kansas: U.S. Geological Survey Water-Supply Paper 1982, 113 p.
- Leonard, R. B., 1970, Effect of irrigation on the chemical quality of ground and surface water, Cedar Bluff Irrigation District, Kansas. Relationship of Agriculture to Soil and Water Pollution, Cornell University, p. 147-163.
- Leonard, R. B., and Morgan, C. O., 1970, Application of computer techniques to seepage-salinity surveys in Kansas: Kansas Geological Survey Spec. Distrib. Pub. 47, 44 p.
- Leonard, R. B., Diaz, A. M., and Broeker, M. E., 1969, Chemical quality of the streamflow of the Whitewater and West Branch Whitewater Rivers near Towanda, Kansas, U.S. Geol. Survey Adm. Report, 1967-69, 41 p.
- Leonard, R. B., 1969, A sampler for small diameter wells: WRD Bull., Oct.-Dec. 1969, p. 24.
- Leonard, R. B., 1969, Time of travel study on the Big Blue River: Kansas Water News, Kansas Water Resources Board, v. 12, no. 3, p. 7-8.

Bibliography - Robert B. Leonard

- Leonard, R. B., 1969, Effect of irrigation on the chemical quality of low stream-flow adjacent to Cedar Bluff Irrigation District, Kansas, a progress report: Kansas State Department of Health Bull. 1-10, 17 p.
- Leonard, R. B., 1969, Variations in the chemical quality of ground water beneath an irrigated field, Cedar Bluff Irrigation District, Kansas, an interim report: Kansas State Department of Health Bull. 1-11, 20 p.
- Leonard, R. B., and Burns, C. V., 1968, Review of seepage-salinity investigations in the South Fork Solomon River and Prairie Dog Creek: U.S. Geological Survey Adm. Report, 23 p.
- Furness, L. W., Albert, C. D., Leonard, R. B., 1967: Kansas River, Bonner Springs to Mouth. Degradation of Channel: U.S. Geological Survey Adm. Report, Feb., 18 p.
- Leonard, R. B., 1964, Cooperative water quality investigation of the Walnut River Basin: Kansas Water News, State Water Resources Board, August, 2 p.
- Leonard, R. B., and Shah, K. L., 1964, The relation of the chemical quality of the Whitewater River at Towanda to that of the Walnut River at Winfield, Kansas, during the 1963 water year: Kansas State Department of Health, Environmental Health Services Bull. 1-2, 18 p.
- Leonard, R. B., 1964, Results of four chemical-quality surveys of the Walnut River Basin, Kansas (Dec. 1961 to Oct. 1963): Kansas State Department of Health, Environmental Health Services Bull. 1-3, 38 p.
- Leonard, R. B., 1964, A method for evaluating oil-field brine pollution of the Walnut River in Kansas: U.S. Geological Survey Prof. Paper 501-B, p. B173-B176.

Resume'

Donald DeMar Runnells

Personal

Birthdate: December 30, 1936
Birthplace: Eureka, Utah, U.S.A.
Marital: Married, two children

Academic Record

B.S.	1958	University of Utah	Geology	High Honors
M.A.	1960	Harvard University	Geology	
Ph.D.	1964	Harvard University	Geology	

Professional Positions

1961-1962	Teaching Assistant Harvard University
1963-1965	Geochemist Shell Development Company Houston, Texas
1965-1967	Geochemist Shell Development Company Coral Gables, Florida
1967-1969	Assistant Professor University of California Santa Barbara, California
1969-1975	Associate Professor University of Colorado Boulder, Colorado
1975-present	Professor University of Colorado Boulder, Colorado

Temporary positions -- seven summers with mining companies.

Professional Societies

Geological Society of America (Fellow)
Society of Economic Paleontologists and Mineralogists
Association of Exploration Geochemists
National Water Well Association -- Technical Division
Soil Science Society of America

Administrative Positions

Associate Director, The Molybdenum Project, University of Colorado, NSF-Rann, 1971-1975.

Co-director, Trace Elements in Oil Shale, University of Colorado, U. S. Dept. of Energy, 1976-1978.

Graduate Admissions Committee, Department of Geological Sciences, University of Colorado.

Chairman, Departmental Search Committee, Position in Economic Geology, University of Colorado, 1976-1977.

Executive Committee, Department of Geological Sciences, University of Colorado.

Summer Departmental Chairman, University of Colorado, 1973, 1987.

University Appeals Committee on Academic Rules and Procedures, 1976-1979, 1983-1986

Chairman of Departmental Lecture Series, University of Colorado, 1984.

Board of Directors, Colorado Energy Corporation, Boulder, Colorado, 1972-1974.

Board of Directors, Grayhill Exploration Co., Arvada, Colorado, 1981-1985.

Faculty Assembly (elected position), University of Colorado, 1987-1990.

Other Academic and Professional Positions

Publications Committee, Association of Exploration Geochemists, 1969-1971.

Committee on Public Policy, Geological Society of America, 1976-1979.

Program Committee, Colorado Scientific Society, 1973-1974.

Site Review Team, NSF-RANN, Stanford University and the University of California, 1973.

Organizer, Symposium on Environment and Public Policy, Geological Society of America Annual Meeting, Denver, 1976.

Advisory Committee, Penrose Conference on Carbonate-Water Interactions, Vail, Colorado, 1973.

Other Academic and Professional Positions (continued)

Co-organizer, Symposium on Geochemical Exploration for Uranium, Geological Society of America Annual Meeting, San Diego, 1979.

Co-Organizer, Symposium on Environmental Impact of Uranium Mill Effluents, Geological Society of America, San Diego, 1979.

Headquarters Committee, Geological Society of America, Boulder, Colorado, 1980-1983.

Instructor, Course on Ground Water Chemistry, New Mexico Environmental Improvement Division, Santa Fe, May, 1980.

Instructor, Course on Aquifer Restoration, EPA Regional Offices, Dallas, Texas, July, 1983.

Faculty Sponsor, Short course in ground water monitoring: National Water Well Association, Technical Division: University of Colorado, Boulder, 1984.

Consulting Positions

Anaconda Minerals Co., Denver, Colorado.

Battelle Memorial Institute, Columbus, Ohio.

Battelle Pacific Northwest Laboratory, Richland, Washington.

New Mexico Environmental Improvement Division, Santa Fe.

Farmers Investment Company, Sahuarita, Arizona.

County Attorney, Santa Barbara County, California.

Toups Corporation, Los Angeles, California.

Cyprus Bagdad Mining Co., Bagdad, Arizona.

Mobil Research and Development Company, Dallas, Texas.

Exxon Minerals, Inc., Albuquerque, NM and Casper, Wyoming.

Wyoming State Attorney Generals Office, Cheyenne, Wyoming.

Jim Walsh Associates, Boulder, Colorado.

Union Geothermal Company, Rio Rancho, New Mexico.

Water Resources Associates, Phoenix, Arizona.

Rocky Mountain Energy Corporation, Brocmfield, Colorado.

Consulting Positions (continued)

Terra Therma, Inc., Denver, Colorado.

Kerr-McGee Corporation, Oklahoma City, Oklahoma.

Engineering Enterprises, Norman, Oklahoma.

Argonne National Laboratory, Materials Review Board, Argonne, Illinois.

Arizona Attorney General, Phoenix, Arizona.

Water, Waste, and Land, Inc., Ft. Collins, Colorado.

Professional Recognition and Honors

Listed in Who's Who in the West, American Men and Women of Science, and Who's Who in Science and Technology.

Phi Kappa Phi Honorary Scholastic Fraternity.

National Science Foundation Graduate Fellow, 1958-1962.

Bachelor's Degree with High Honors, University of Utah, 1958.

Invited Speaker, Colorado Scientific Society, Dec., 1974.

Fellow, Cooperative Institute for Research in the Environmental Sciences, University of Colorado, 1980-1982.

Elected Councillor, Society of Environmental Geochemistry and Health, 1977-1980.

Invited Speaker, University of Virginia, Department of Environmental Sciences, April, 1978.

Elected Councillor, Association of Exploration Geochemists, 1980-present.

Regional Editor, Journal of Geochemical Exploration, 1971-1975.

Soils Editor, Interface, (Soc. Environ. Geochem. Health), 1976-1981.

Invited Speaker, Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, Feb., 1981.

Editorial Board, Science of the Total Environment, 1979-1982.

Editorial Board, Chemical Geology, 1981-present.

Colorado Governor's Council on Science and Technology, ad hoc Committee on Lowry Landfill assessment, 1980.

Professional Recognition and Honors (continued)

Colorado Ground Water Association Legislative Advisory Committee, 1983-1984.

Review Board on Disposal and Permanent Storage of Inactive Uranium Tailings, Sandia National Laboratory, 1980.

Invited Review Board Member, Scientific Aspects of Disposal of Nuclear Wastes, Materials Research Society, 1983 Annual Meeting, Boston.

Invited Chairman, Workshop on Hydrogeochemical Exploration for Mineral Deposits, Association of Exploration Geochemists, Helsinki, Finland, 1983.

Invited Chairman, Workshop on Fundamental Research Needs in Geochemical Modeling of Nuclear Waste Disposal, Los Alamos National Laboratory, 1984.

Invited Participant, Expert Panel on Future Technology in Exploration for Copper Deposits, U. S. Bureau of Mines, Denver, Colorado, September, 1981.

Invited Speaker, Penrose Conference on Geochemical Aspects of Disposal of Nuclear Wastes, Mount Hood, Oregon, 1984.

Appointed Member, Materials Review Board, Argonne National Laboratory, 1980-1984.

Invited speaker, Department of Geology, Brigham Young University, October, 1984.

Invited speaker, Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, May, 1985.

Paper on "Diagenesis, chemical sediments, and the mixing of natural waters" selected for reprinting in 50th Anniversary Volume of the Society of Economic Paleontologists and Mineralogists, 1977, and in Benchmark Papers in Geology, v. 73, Chemical Hydrogeology (Wm. Back and R.A. Freeze, eds.), 1983.

Paper on "Continental drift and economic minerals in Antarctica" reprinted in Benchmark Papers in Geology, v. 44, Mineral Deposits, Continental Drift, and Plate Tectonics (J.B. Wright, ed.), 1977.

Appointed Member, Committee on Ground Water Modeling Assessment: National Research Council, National Academy of Sciences, Water Science and Technology Board, 1987-1988.

Professional Recognition and Honors (continued)

Nominated for Outstanding Professor award at the University of Colorado.

Research Grants and Contracts

Identification of Individual Petroleum Spills by Ratios of Trace Metals, University of California, NSF-Sea Grant Program, \$20,000, 1969.

Geochemistry of Molybdenum, The Molybdenum Project, University of Colorado, NSF-RANN, \$90,000, 1971-1975.

Uranium Reconnaissance in Northeastern and East-Central Colorado, U.S. Department of Energy, \$79,000, 1976-1978.

Mobility of Trace Elements in Oil Shale Leachate, University of Colorado, U.S. Department of Energy, \$53,361, 1979-1980.

Mobility of Trace Elements in Oil Shale Leachate, University of Colorado, U.S. Department of Energy, \$87,827, 1980-1981.

Pollution of Ground Water Due to Inactive Uranium Mill Tailings, Colorado Energy Research Institute, \$2000, 1978-1979.

Contamination of Ground and Surface Waters by Uranium Mining and Milling, U.S. Bureau of Mines, \$44,161, 1979.

Mobilization of Residuals from Colorado Oil Shale, U.S. Department of Energy, \$58,308, 1981-1982.

Release, Transport, and Fate of Potential Pollutants, U.S. Department of Energy, \$69,002, 1983.

Determination of Distribution Coefficients Appropriate for Modeling Contaminant Migration from Energy Residual Wastes, U.S. Department of Energy, 1984, \$60,298; 1985, \$26,543; 1986, \$5000.

Geochemistry of Water-Sediment System, Orinoco River, Venezuela (with Wm. Lewis, Biology Dept.), NSF, approximately \$27,000, 1983-1984.

Evaluation of Thermodynamic Data for Computer Modeling, Lawrence Livermore National Laboratory, \$13,000, 1984.

Hydrology and Chemistry of Interstitial Fluids, Yucca Mountain, Nevada Test Site, U.S. Geological Survey, \$103,683, 1985-1987.

Research Contracts and Awards (continued)

Reversibility of Oxidation-Reduction Reactions in Ground Waters, Applied to the Measurement of Eh and the Modeling of the Chemical Behavior of Nuclear Wastes in Geologic Repositories, Rockwell International-U.S. Department of Energy, \$238,570, 1985-1987.

Transport and Fate of Redox-Sensitive Elements in Ground Water, Electric Power Research Institute, \$249,936. 1987-1989.

Publications (abstracts not included)

1964, Cymrite in a copper deposit, Brooks Range, Alaska: Amer. Mineralogist, v. 49, p. 158-165.

1965, A conductometric method for determining the alkalinity of fresh water: Limnol. and Oceanogr., v. 10, p. 296-298.

1965, Anthraxolite derived from indigenous organic matter in Middle Devonian dolomite, Cosmos Hills, Alaska: Jour. Sed. Petrol., v. 38, p. 599-603.

1969, Diagenesis, chemical sediments, and the mixing of natural waters: Jour. Sed. Petro., v. 39, p. 1188-1202.

1969, Diagenesis due to mixing of natural waters - a hypothesis: Nature, v. 224, p. 361-363.

1969, Mineralogy and sulfur isotopes of the Ruby Creek copper prospect, Bornite, Alaska: Econ. Geol., v. 63, p. 75-90.

1970, Errors in x-ray analysis of mixtures of rhombohedral carbonates due to compositional variation among the component minerals: Jour. Sed. Petrol., v. 40, p. 1158-1166.

1970, Continental drift and economic minerals in Antarctica: Earth and Planetary Sci. Letters, v. 8, p. 400-402.

1971, A reconnaissance study of uranium in the South Platte River, Colorado: Econ. Geol., v. 66, p. 435-450 (with W. W. Boberg).

1971, Chemical weathering in the Biscayne aquifer, Dade County, Florida: Southeastern Geology, v. 13, p. 167-174.

1972, Book Review - Principles of Chemical Sedimentology, by R.A. Berner: Science, v. 175, p. 406.

1973, Nature of soft-tissue calcification in uremia: Kidney International, v. 4, p. 229-235. (with S.R. Contiguglia, A.C. Alfrey, N.L. Miller, and R.Z. LeGeros).

Publications (continued)

- 1974, Detection of molybdenum enrichment in the environment through comparative study of stream drainages, central Colorado: in Proc. Conf. on Trace Substances in Environmental Health, VII, (D.D. Hemphill, Ed.), Univ. Missouri, Columbia, June 12-14, p. 99-104.
- 1974, Comments on direct panspermia: *Icarus*, v. 21, p. 513-515 (with W.R. Chappell and R.R. Meglen).
- 1974, Recent dedolomitization and the origin of the rusty crusts of Northumberland - a discussion: *Jour. Sed. Petrol.*, v. 44, p. 270-271.
- 1974, Investigation of enrichment of molybdenum in the environment through a comparative study of stream drainages, central Colorado, in Proc. of First Annual N.S.F. Trace Contaminants Conf., Oak Ridge, Tenn., Aug. 8-10, (W. Fulkerson, Ed.), p. 599-614 (with D.S. Brown and R.D. Lindberg).
- 1975, Molybdenum in the environment - an interdisciplinary approach: in Geol. Soc. Amer. Spec. Paper 155 (J. Freedman, Ed.), p. 61-72 (with W.R. Chappell and R.R. Meglen).
- 1975, A statistical analysis and computer display of the distribution of molybdenum between alpine soils and plants, in Proc. Second Annual N.S.F. Trace Contaminants Conf., Asilomar, California, Lawrence Berkeley Laboratory, Calif., (T. Novakov, Chairman), p. 256-268 (with F.W. Briesse and E. Smith).
- 1975, Experimental study of sorption of Mo by desert, agricultural, and alpine soils, in Trace Substances in Environmental Health, v. VIII, Columbia, Missouri (D.D. Hemphill, Ed.), p. 107-114 (with B.G. Katz).
- 1975, Removal of dissolved molybdenum from industrial wastewaters by ferric oxyhydroxide: *Environ. Sci. Technol.*, v. 9, August, p. 744-749 (with G.R. LeGendre).
- 1975, Ability of selected soils to remove molybdenum from industrial wastewaters, in Second Annual N.S.F. Trace Contaminants Conf., Asilomar, California, Lawrence Berkeley Laboratory, Calif., (T. Novakov, Chairman), p. 216-223 (with B.G. Katz).
- 1976, Boulder, a sight to behold, guidebook: Publ. by author, 93 pp. (Second Edition, 1980, Johnson Publ. Co., Boulder, Colorado).
- 1976, Wastewater in the vadose zone of arid regions: geochemical interactions: *Ground Water*, v. 14, no. 16, p. 374-385.

Publications (continued)

- 1976, Diagenesis, chemical sediments, and the mixing of natural waters: reprinted in Sedimentary Processes, Diagenesis, Soc. Econ. Paleon. and Mineral. Reprint Series No. 1, (D.M. Curtis, Ed.), p. 193-206.
- 1977, Geochemistry and sampling of molybdenum in sediments, soils, and plants in Colorado, in Molybdenum in the Environment, v. 2 (W.R. Chappell and K.K. Peterson, Eds.), Marcel-Dekker, N.Y., p. 387-423 (with D.S. Kaback and E.M. Thurman).
- 1977, Leachability of arsenic, selenium, molybdenum, boron, and fluoride from retorted oil shale in Proc. Second Pacific Chem. Engin. Congress, Denver, Colorado, Aug. 28-31, 8 pp. (with K.G. Stollenwerk).
- 1977, Toxic trace elements and oil shale production, in Trace Substances in environmental health, v. XII, Columbia, Missouri (D.D. Hemphill, Ed.), p. 383-388 (with W.R. Chappell).
- 1977, Continental drift and economic minerals in Antarctica, Earth and Planet. Sci. Letters, v. 8, p. 400-402, reprinted in Benchmark Series in Geology, v. 44, Mineral Deposits, Continental Drift, and Plate Tectonics (J.B. Wright, ed.), Stroudsburg, Pennsylvania, p. 50-52.
- 1978, Important goals for new geologists: Geol. Soc. Amer. News and Information, January, p. 28.
- 1979, Base study of the concentration of molybdenum in stream sediments of the major rivers in Colorado, U.S.A.: Jour. Geochem. Explor., v. 11, p. 249-261 (with R.M. Thurman).
- 1980, Geochemistry of molybdenum in some stream sediments and waters, distribution and character: Geochim. et Cosmochim. Acta, v. 44, p. 447-456 (with D.S. Kaback).
- 1980, Applications of computer modeling to the genesis, exploration, and in-situ mining of uranium and vanadium deposits: New Mex. Bur. Mines and Mineral. Res., Memoir 38, p. 355-367 (with R.D. Lindberg, S.L. Lueck, and G. Markos).
- 1980, Geochemistry of fluorine in oil shale leachates: Proc. 13th Annual Oil Shale Symposium, Colorado School of Mines, Golden, Colorado, (J.H. Gary, Ed.), p. 362-368 (with O.M. Saether).
- 1981, Hydrogeochemical exploration for uranium ore deposits: use of the computer model WATEQFC: Jour. Geochem. Explor., v. 15, p. 37-50 (with R.D. Lindberg).

Publications (continued)

- 1981, Fluorine: its mineralogical residence in the Mahogany zone of the Green River Formation, Piceance Creek Basin, Colorado, U.S.A.: *Chemical Geology*, v. 31, p. 169-184 (with O.M. Saether, R.A. Ristinen, and W.R. Smythe).
- 1981, Geochemistry and environmental impact of aqueous leachates from Colorado oil shale: *Environ. Sci. Technol.*, v. 15, no. 11, p. 1340-1346 (with K. Stollenwerk).
- 1982, Interaction of Tosco II leachate with weathered Uinta formation in the Piceance Creek Basin, Colorado: 15th Annual Oil Shale Symposium, Colorado School of Mines, Golden, Colorado, (J.H. Gary, Ed.), p. 529-544 (with E. Esmaili).
- 1983, Diagenesis, chemical sediments, and the mixing of natural waters: reprinted in *Benchmark Papers in Geology* 73, *Chemical Hydrogeology* (W. Back and R.A. Freeze, Eds.), Hutchinson Ross Publ. Co., Stroudsburg, Pennsylvania, p. 129-142.
- 1983, Contamination of ground and surface waters by uranium mining and milling, v. III: experimental studies and analytical procedures: *Minerals Res. Contract Rept.*, U.S. Bureau of Mines, U.S. Dept. of Interior, Minneapolis, Minnesota, 229 pp. (senior author, with junior authors C.N. Gerlitz, A.O. Davis, R.D. Lindberg, R. Meglen, G. Swanson, L. Taylor, R. Sistko, and R. McNelly).
- 1983, Computer modeling of the interaction of leachate from Tosco II oil shale with weathered Uinta Formation: 16th Annual Oil Shale Symposium, (J.H. Gary, Ed.), Colorado School of Mines, Golden, Colorado, p. 602-611 (with E. Esmaili and D. Axtell).
- 1984, The mobility of uranium and associated trace elements in the Bates Mountain tuff, central Nevada: *Econ. Geol.*, v. 79, p. 558-564 (with J.A. Kizis, Jr.).
- 1984, Summary of the workshop on Hydrogeochemistry in Mineral Exploration: Helsinki, Finland, Aug. 29-Sept. 2, 1983: *Jour. Geochem. Explor.*, v. 21, no. 1-3, p. 129-132.
- 1984, Review panel comments on geomeia-specific research: in *Scientific Basis for Nuclear Waste Management VII*: (G. L. McVay, Ed.), *Materials Res. Soc. Sympos. Proc.*, v. 26, p. 459-460.
- 1984, Book Review - Carbonates: Mineralogy and Chemistry (R.J. Reeder, Ed.): *Reviews in Mineralogy*, Vol. 11, *Mineral. Soc. Amer.: Jour. Sed. Petrol.*, v. 54, no. 3, p. 1040-1041.

Publications (continued)

- 1984, Groundwater redox disequilibrium: applications to measurement of Eh and computer modeling: Science, v. 225, 31 August, p. 925-927 (with R.D. Lindberg).
- 1984, Trace and minor elements in Colorado oil shale, concentrated by differential density centrifugation: Chemical Geology, v. 47, no. 1/2, p. 1-14 (with O.M. Saether and R.R. Meglen).
- 1985, Book Review - Mineralogical Association of Canada Short Course in Environmental Chemistry, ed. by M.E. Fleet: Geochim. et Cosmochim. Acta, v. 49, no. 10, p. 2193.
- 1985, Modeling, Chapter in Workshop on Fundamental Geochemistry Needs for Nuclear Waste Isolation - June 20-22, 1984. Los Alamos National Lab., New Mexico, (B.R. Erdal, Chairman; J. H. Heiken, Editor): U.S. Dept. of Energy Publication CONF8406134, p. 59-67.
- 1985, Determining the reversibility of oxidation-reduction reactions in groundwater: Rockwell Hanford Operations, BWIP Supporting Doc. SD-BWI-TI-309, Richland, WA, 45 pp. (with R.D. Lindberg and J.H. Kempton).
- 1986, Application of flow, mass transport, and chemical reaction modeling to subsurface liquid injection: Proceeds. of International Sympos. on Subsurface Injection of Wastes: New Orleans, LA, March 3-5: Water Well Jour. Publ. Co., Dublin, Ohio, p. 447-463 (with T.A. Prickett and D.L. Warner).
- 1986, Evaluation of the validity and statistical variability of lithium and fluoride distribution coefficient values in a complex geochemical system: U.S. Dept. Energy Research Highlights Rept. ER-0261, Office of Energy Research, Ecological Research Div., Washington, DC, 16 pp (with Hannah Pavlik).
- 1986, Book Review - Applied Environmental Geochemistry, edited by Iain Thornton: Academic Press Geology Series, Academic Press, New York: Jour. Geochem. Explor., v. 25, p. 404-405.
- 1986, A laboratory study of electromigration as a possible field technique for the removal of contaminants from ground water: Ground Water Monitoring, v. 6, no. 3, p. 85-91 (with J.L. Larson).
- 1987, Low-Temperature Geochemistry: Chapter 6 in Volume 6, Encyclopedia of Science and Technology, : Academic Press, San Diego, CA, p. 36-62.

Publications (continued)

- 1987, American research in the geochemical modeling of ground water: Journal Geol. Soc. India, v. 29, no. 1, p. 135-144.
- 1987, Irreversibility of Se(VI)/Se(IV) redox couple in synthetic basaltic ground water at 25°C and 65°C: in Proc. Scientific Basis for Nuclear Waste Management VIII, Mater. Research Soc., v. 84, North Holland Publ., p. 723-733 (with R.D. Lindberg and J.H. Kempton).
- 1987, Geochemical interactions between uranium tailings fluids and subjacent bedrock: Applied Geochemistry, v. 2 (with Andy Davis) (in press)